



東南大學  
SOUTHEAST UNIVERSITY

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# The 25<sup>th</sup> International Conference on Fluidized Bed Conversion

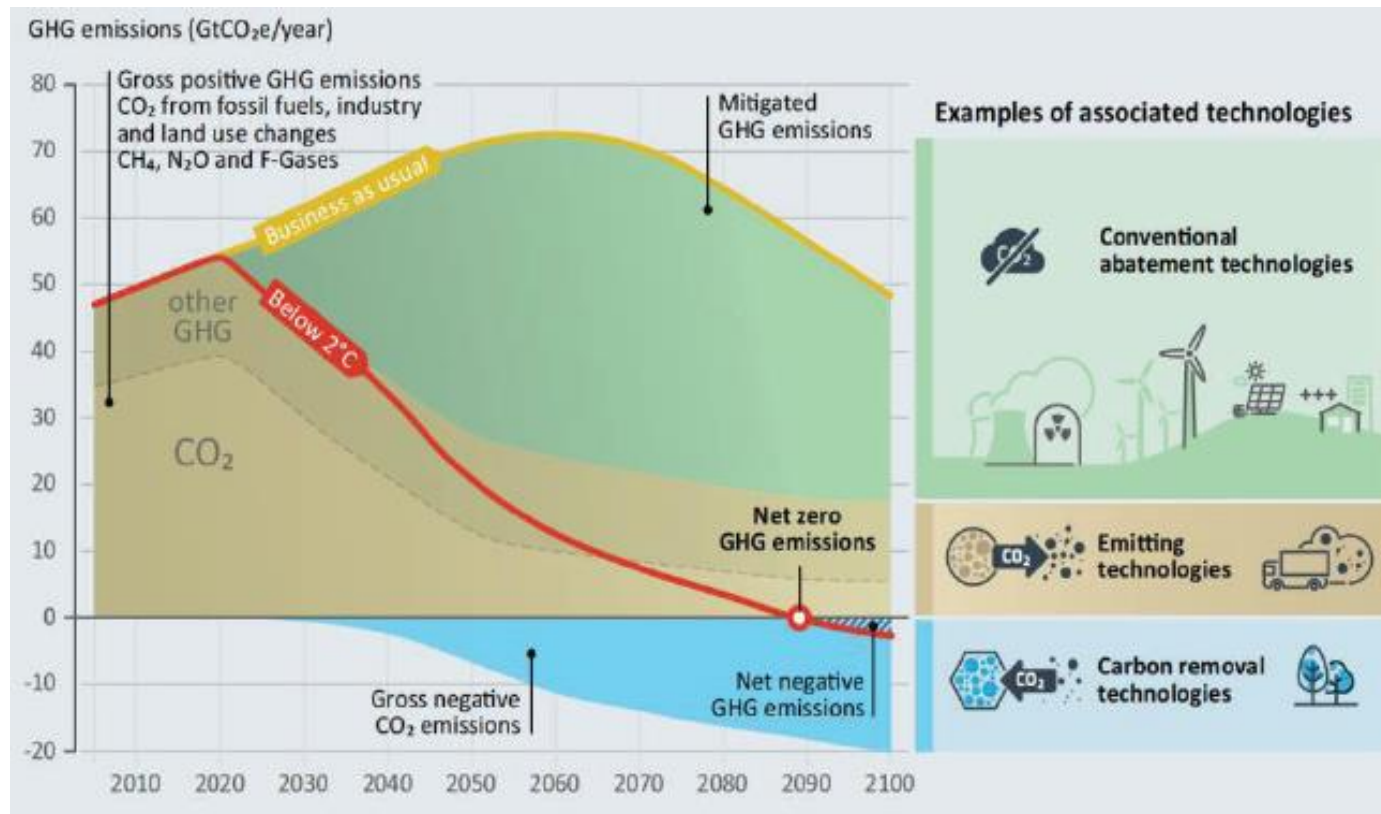
## Exploring Fluidized-Bed Reactor Designs in Chemical Looping Systems

**F. García-Labiano**

Consejo Superior de Investigaciones Científicas (CSIC)  
- Instituto de Carboquímica (ICB), Zaragoza, Spain -



The Paris Agreement's target is to **limit global warming to well below 2°C** above pre-industrial levels, and to pursue efforts to limit it to 1.5°C. The agreement also aims to reduce greenhouse gas emissions and **achieve net zero emissions** in the second half of the century



Source: © Credit UNEP 2017



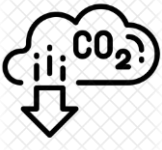
## 1. Reducing Greenhouse Gas Emissions

- CCS helps reduce CO<sub>2</sub> emissions from industries like power plants, cement, and steel production, which are hard to decarbonize.



## 2. Meeting Climate Targets

- The IPCC (Intergovernmental Panel on Climate Change) and IEA (International Energy Agency) emphasize that CCS is crucial for reaching net-zero emissions by 2050.
- Without CCS, it will be extremely difficult to limit global warming to 1.5°C or 2°C above pre-industrial levels.



## 3. Decarbonizing Fossil Fuel Use

- While renewable energy is growing, many countries still rely on coal, oil, and gas for power.
- CCS allows for the continued use of these fuels without releasing CO<sub>2</sub> into the atmosphere.



## 4. Enabling Negative Emissions

- CCS is essential for Direct Air Capture (DAC) and Bioenergy with CCS (BECCS), which remove CO<sub>2</sub> from the atmosphere.
- These technologies help offset emissions that are hard to eliminate (e.g., from aviation or agriculture).



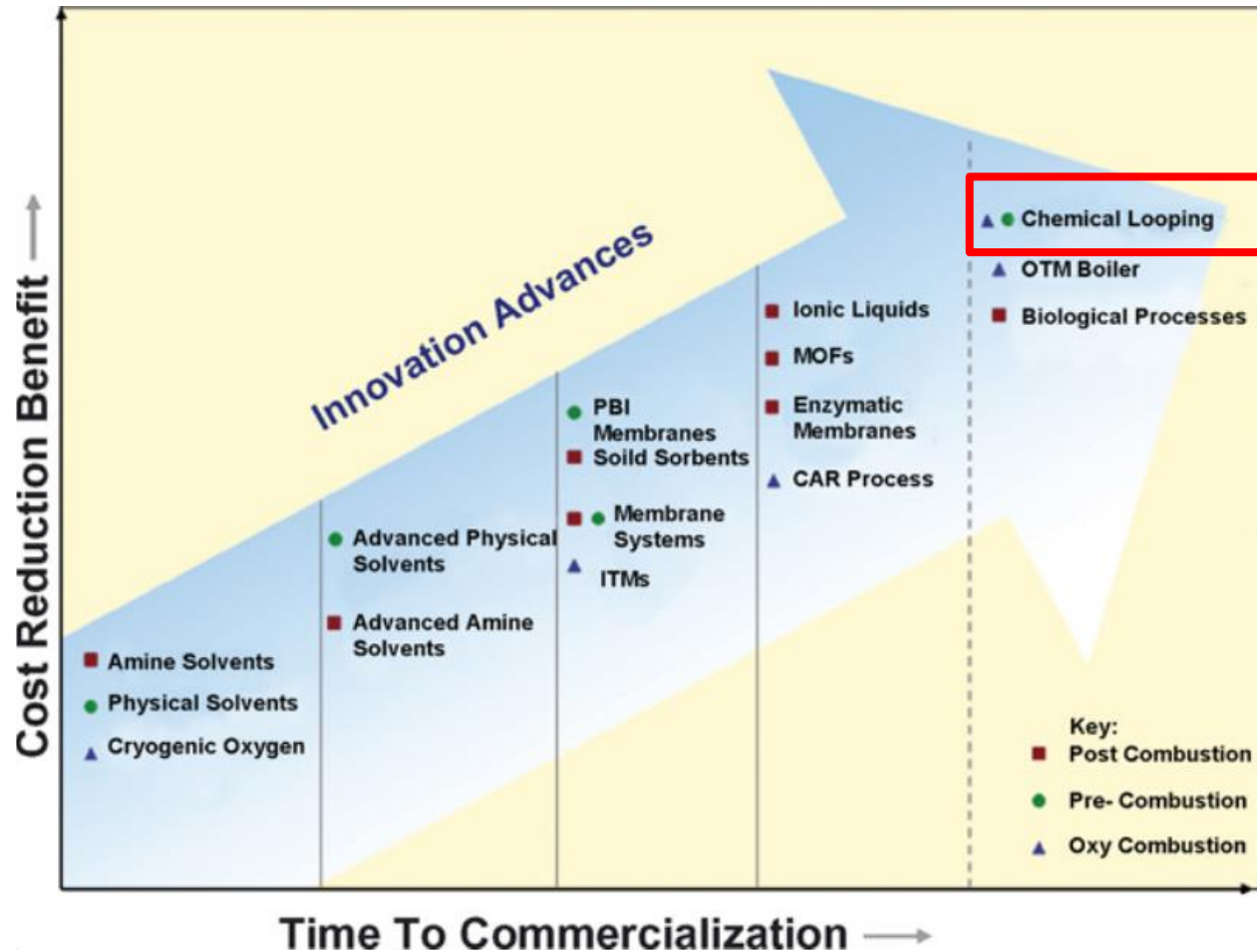
## 5. Supporting Industrial Decarbonization

- Some industries (e.g., cement, steel, chemicals) produce CO<sub>2</sub> as part of their chemical processes, not just from burning fuel.
- CCS is one of the few ways to cut emissions in these sectors.



## 6. Providing a Transition Strategy

- CCS helps balance economic growth and climate action, allowing industries to transition without major disruptions.
- It provides a bridge between fossil fuels and a fully renewable energy future.



**Chemical Looping** was considered one of the most promising technologies for Carbon Capture.

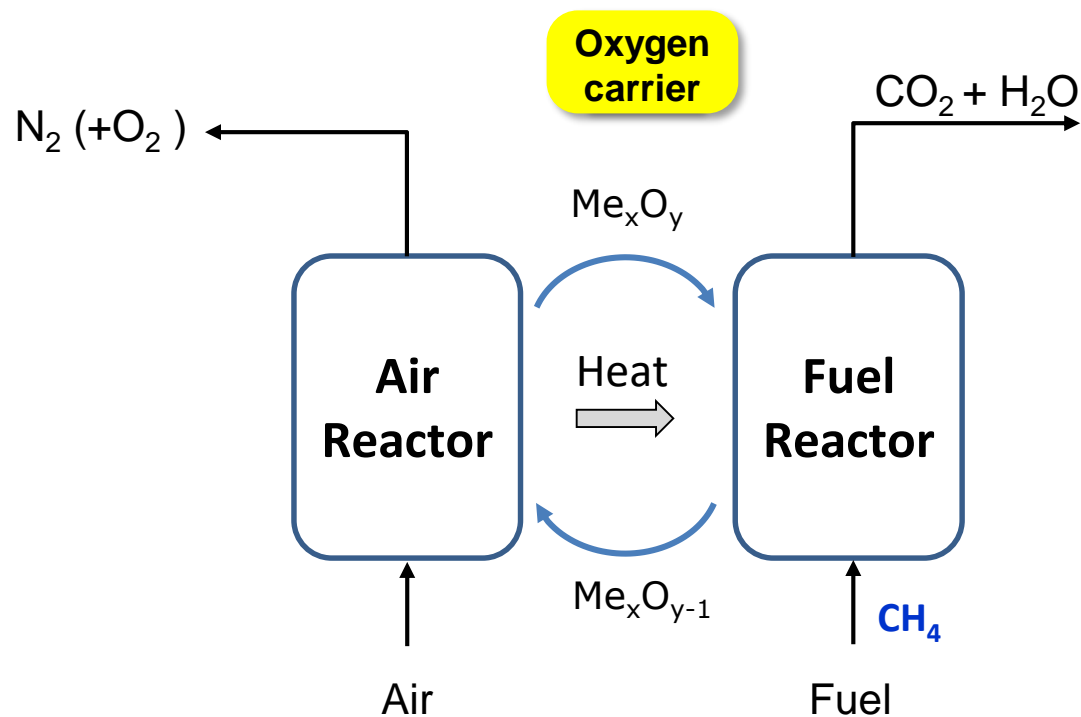
Fuente: Figueroa et al., 2008

During the last 25 years

Have we move forward correctly?

Do we have the knowledge to do commercial the CL  
in the next future?

- **Chemical looping concept and keypoints**
  - oxygen carrier, solids circulation rate, heat transfer, solids inventories
- **Chemical looping continuous units**
  - CLC gaseous fuels
  - CLC liquid fuels
  - CLC solid fuels
    - design solutions to improve CO<sub>2</sub> capture & oxygen demand
    - semiindustrial units (TUDA, Chalmers, Deyang –Cheers-)
- **Scale up**
- **New challenges in CL technologies** (BECCS, CLG –biofuels-, ..)

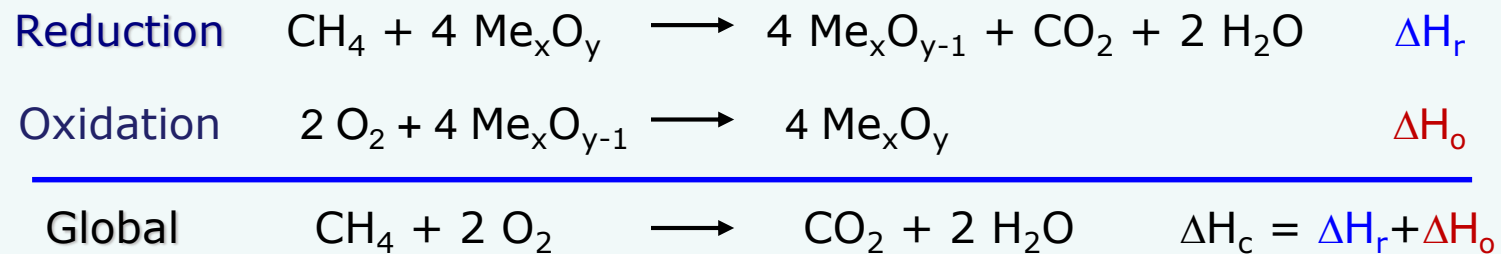


### What is needed?

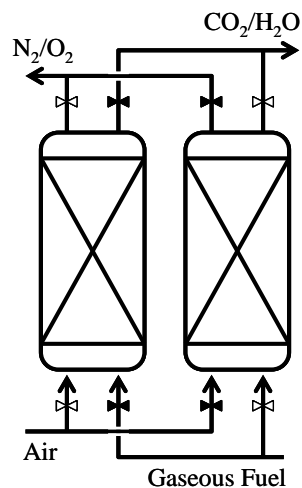
Oxygen transfer

Heat transfer

Good gas-solid contact



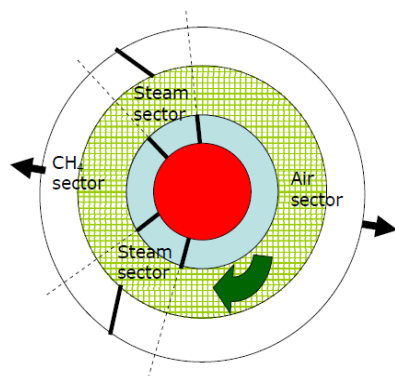
Moves gases



**Alternating fixed beds**

- Pressurised systems
- Difficult heat control
- Complex scale-up

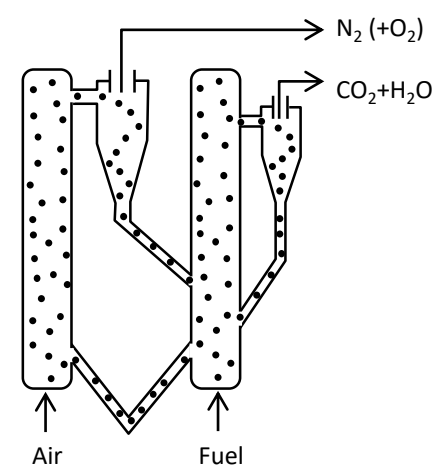
Moves the reactor



**Rotary reactor**

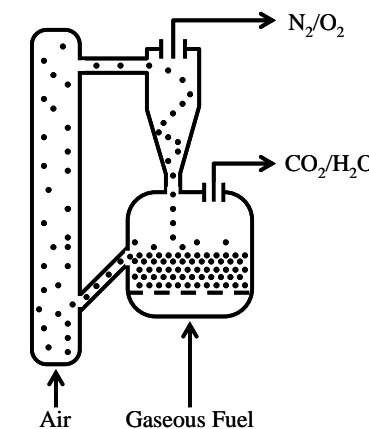
- Difficult operability at high T

Moves Oxygen carrier



**Fluidized beds interconnected**

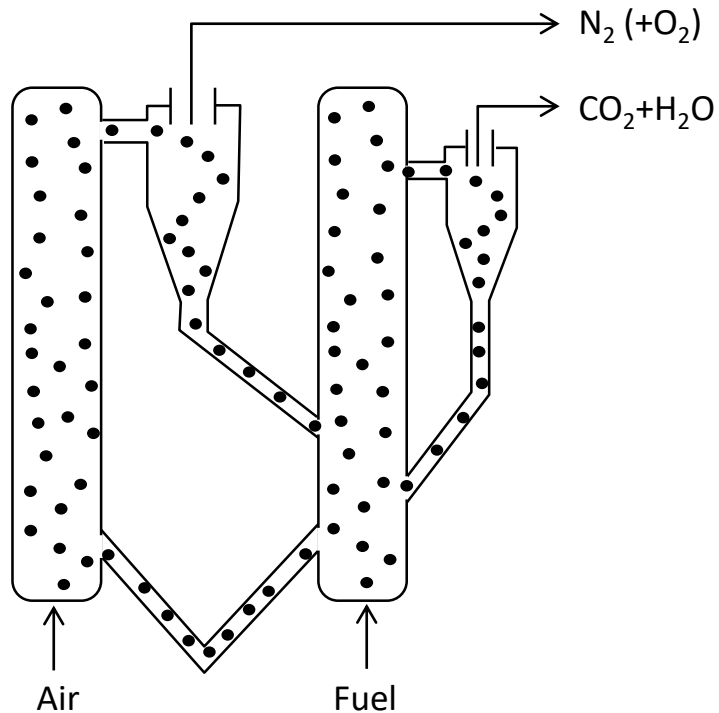
- Good oxygen transference
- Good heat transfer control
- Good gas-solid contact



**Moving-Fluidized beds interconnected**

- dp or gas flow should be optimized

**Interconnected Fluidized beds fulfill all the requirements needed.**



1. The **circulation rate** between the reactors, that must be high enough to transfer the **oxygen** necessary for the fuel combustion and the **heat** necessary to maintain the heat balance
2. The **amount of bed material** in the two reactors, that must be adequate for a sufficient conversion of reacting gas

## The oxygen-carrier characteristics:

- (i) sufficient oxygen transport capacity
- (ii) favourable thermodynamics regarding the fuel conversion to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  in CLC
- (iii) high reactivity for reduction and oxidation reactions, to reduce the solids inventory in the reactors, and maintained during many successive redox cycles
- (iv) resistance to attrition to minimize losses of elutriated solids
- (v) good fluidization properties (no presence of agglomeration)
- (vi) limited cost
- (vii) environmental friendly characteristics

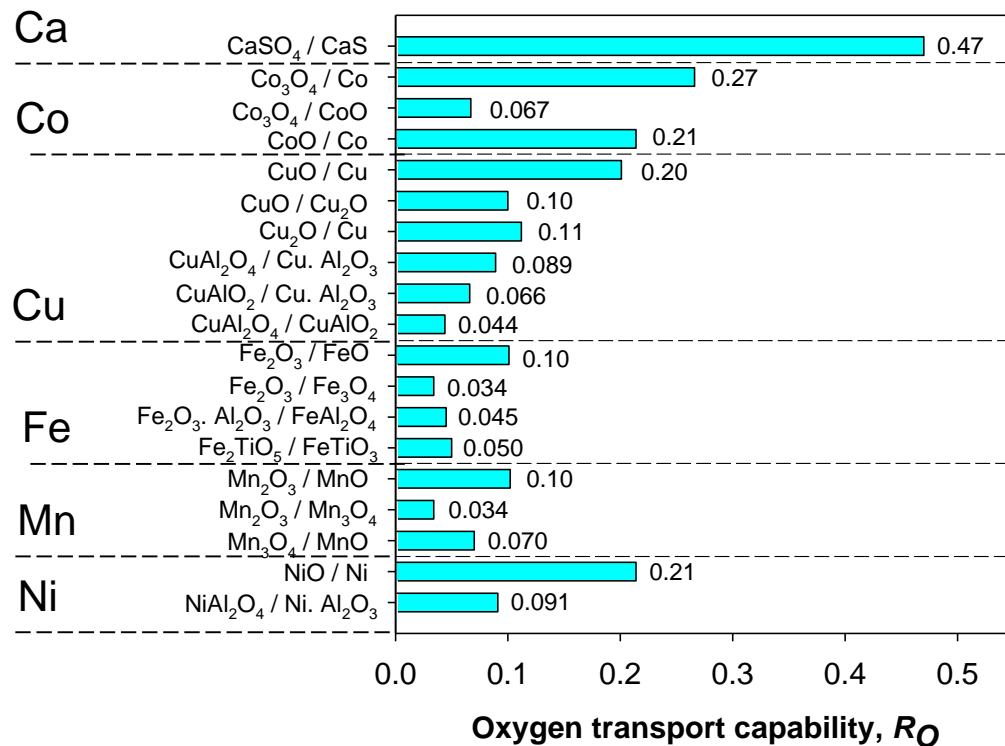


$$R_0 = \frac{m_{ox} - m_{red}}{m_{ox}}$$

$R_0$  means the oxygen transport capacity of a redox pair MeO/Me

$$R_{OC} = R_0 \cdot x_{MeO}$$

$R_{OC}$  means the oxygen transport capacity of an oxygen carrier



## Support

Al<sub>2</sub>O<sub>3</sub>  
MgAl<sub>2</sub>O<sub>4</sub>  
SiO<sub>2</sub>  
TiO<sub>2</sub>  
ZrO<sub>2</sub>

**Solids circulation rate** between the reactors must be high enough

- to transfer the oxygen necessary for the fuel combustion and
- the heat necessary to maintain the heat balance

**Reference:**

1 MW<sub>t</sub>

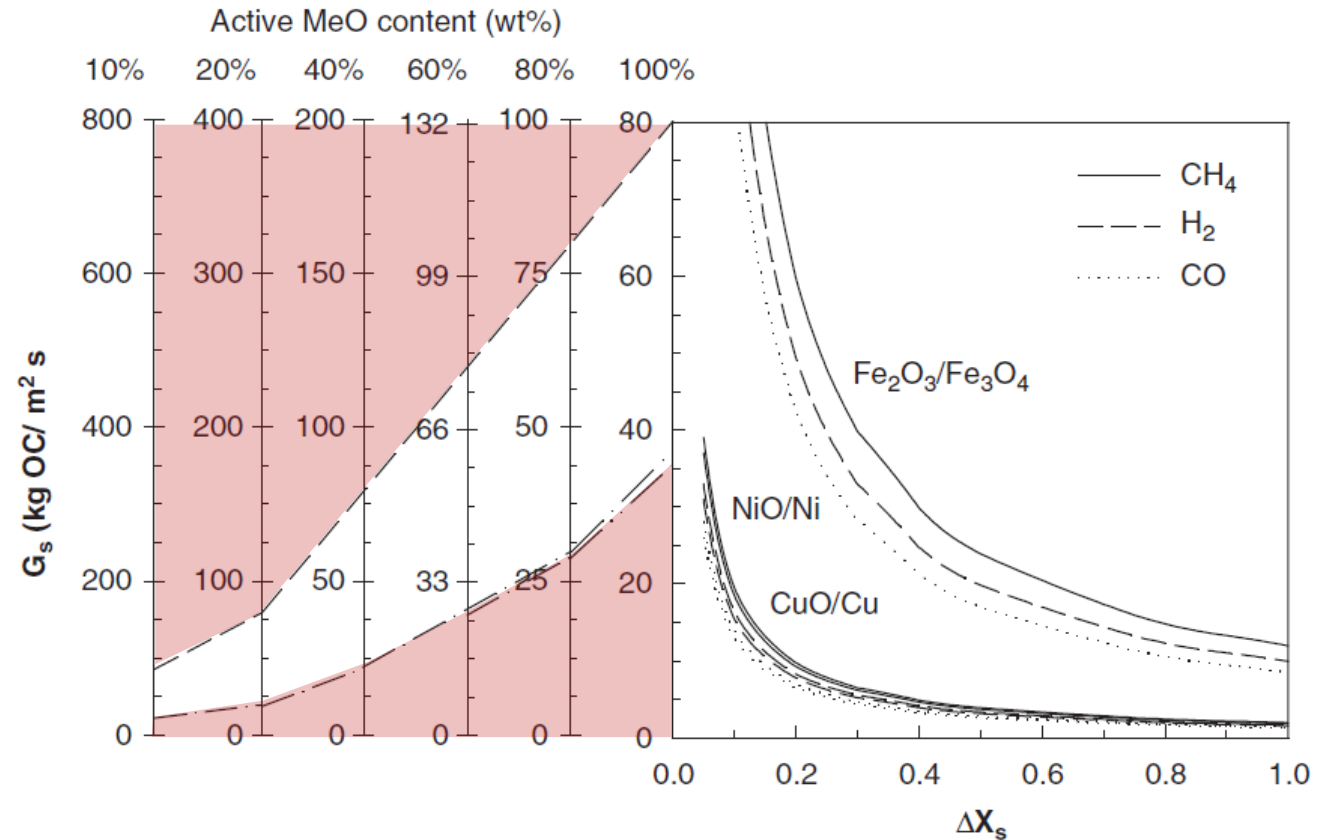
X<sub>gas</sub> = 100%

$$\dot{m} = M_o \frac{1}{R_{o,OC}} \frac{2d}{\Delta H_c^o} \frac{1}{\Delta X_s} \left( \frac{kg_{MeO}}{S.MW} \right)$$

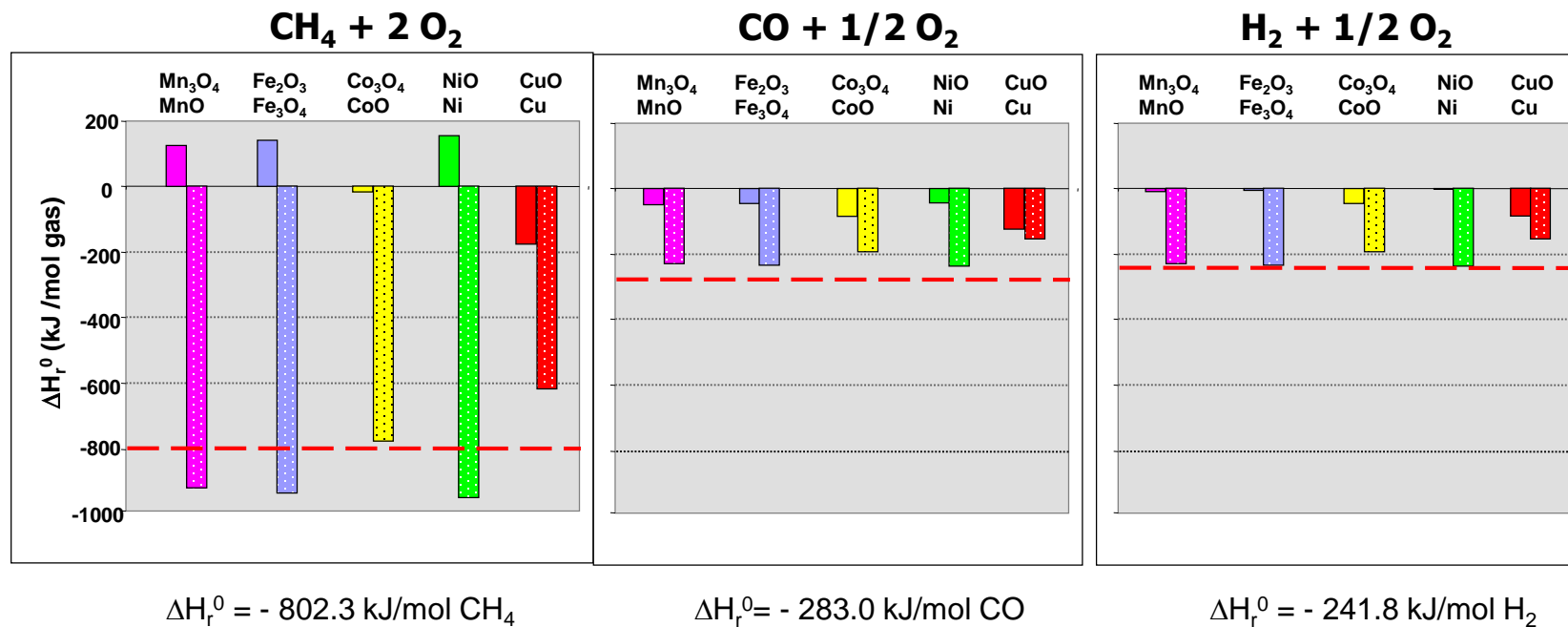
**Oxygen transport capacity**  
Redox pair and Meo content

**Type of gas**

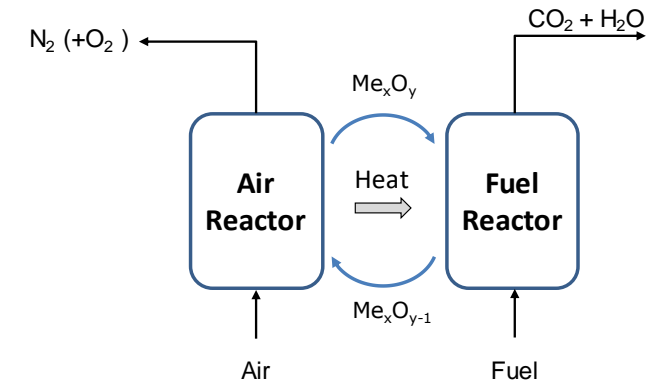
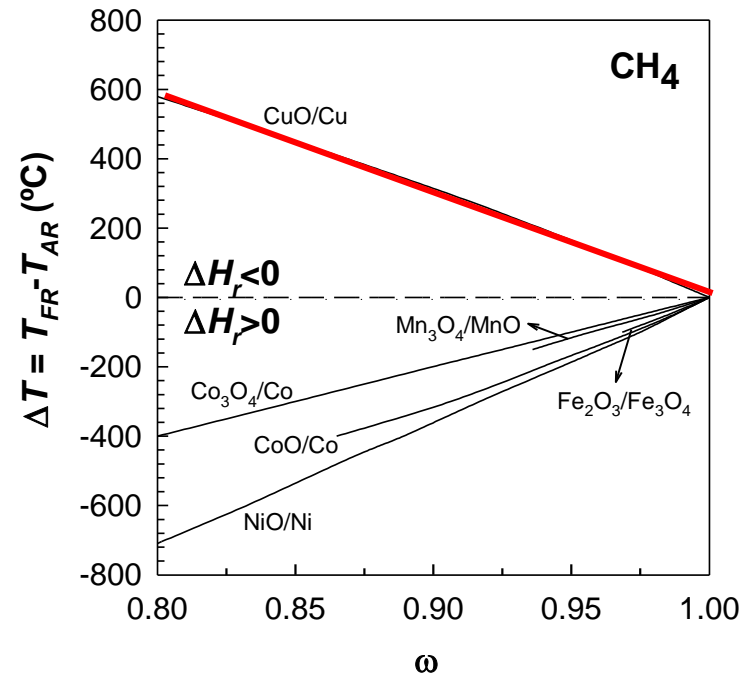
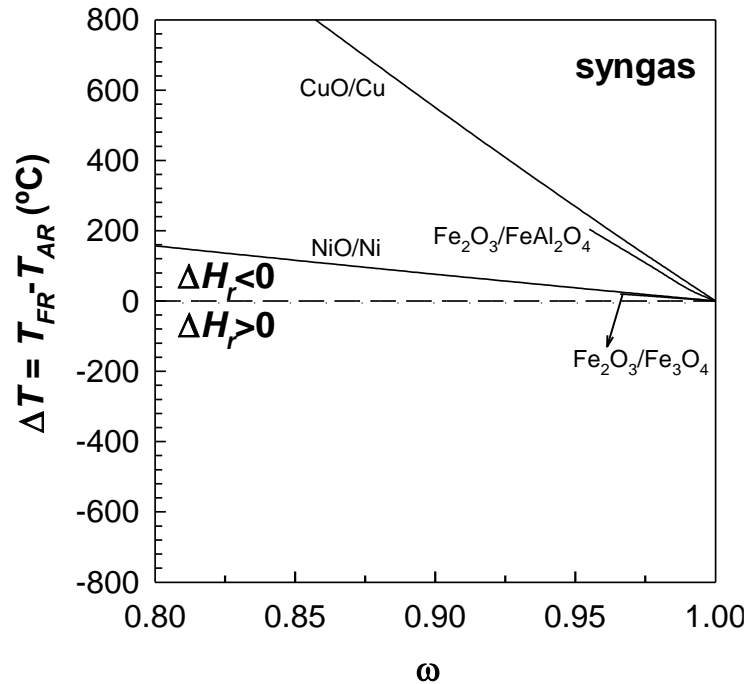
	kJ/mol	mol <sub>t</sub> /s	mol <sub>O</sub> /s
CH <sub>4</sub>	- 802	1.25	5
CO	- 283	3.53	3.53
H <sub>2</sub>	- 242	4.14	4.14



- Enthalpy distribution between reactors depends on the redox pair and fuel



- To fulfil the heat balances there must be a difference of temperature between reactors
- It depends on the oxygen carrier conversion  $\omega$  ( $\omega = R_{OC} \cdot \Delta X_s$ )



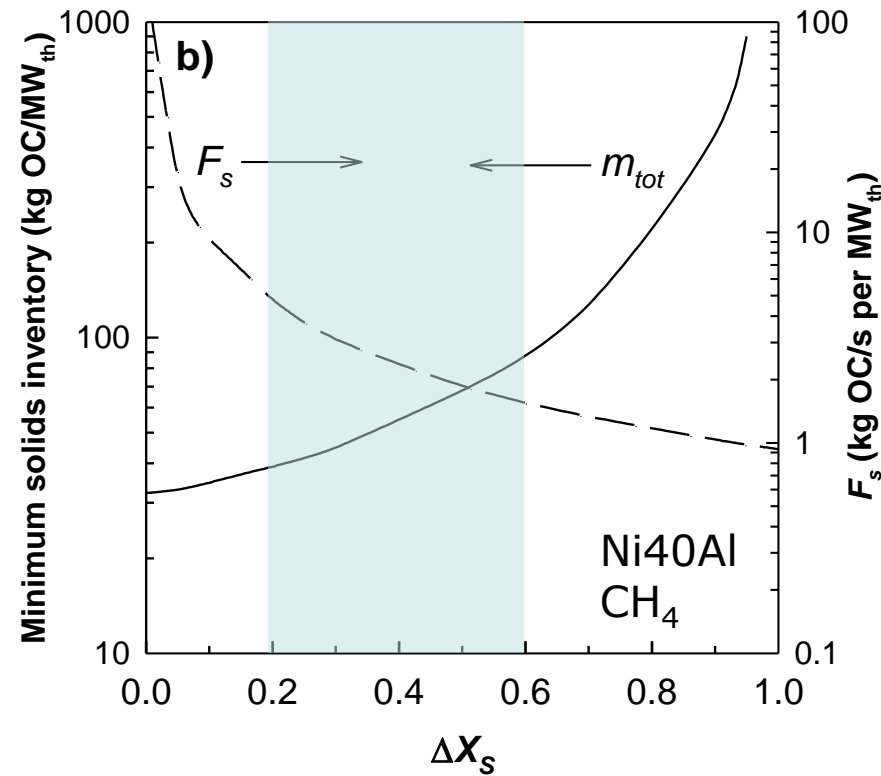
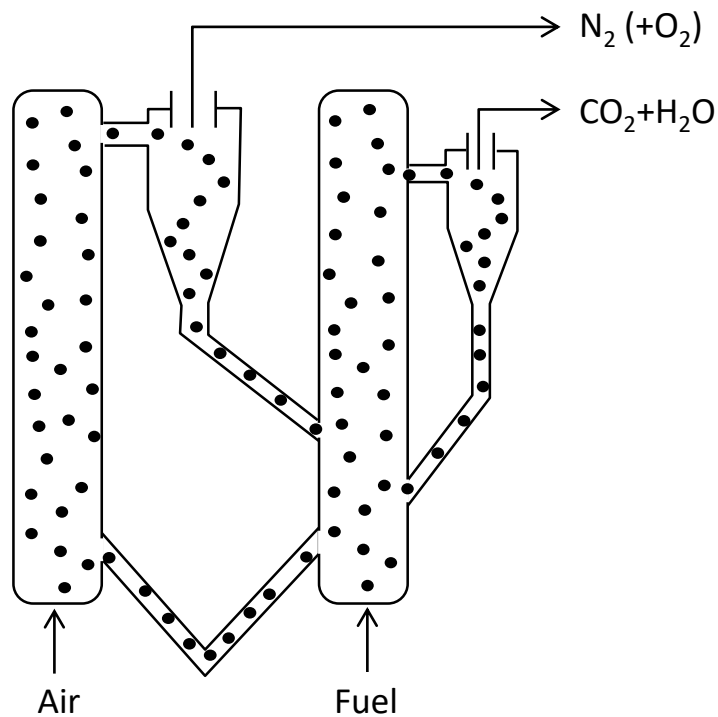
- High  $T_{AR}$  should be avoided (1100 °C)
- To maintain energy balance, heat must be removed from the AR (or between FR and AR)

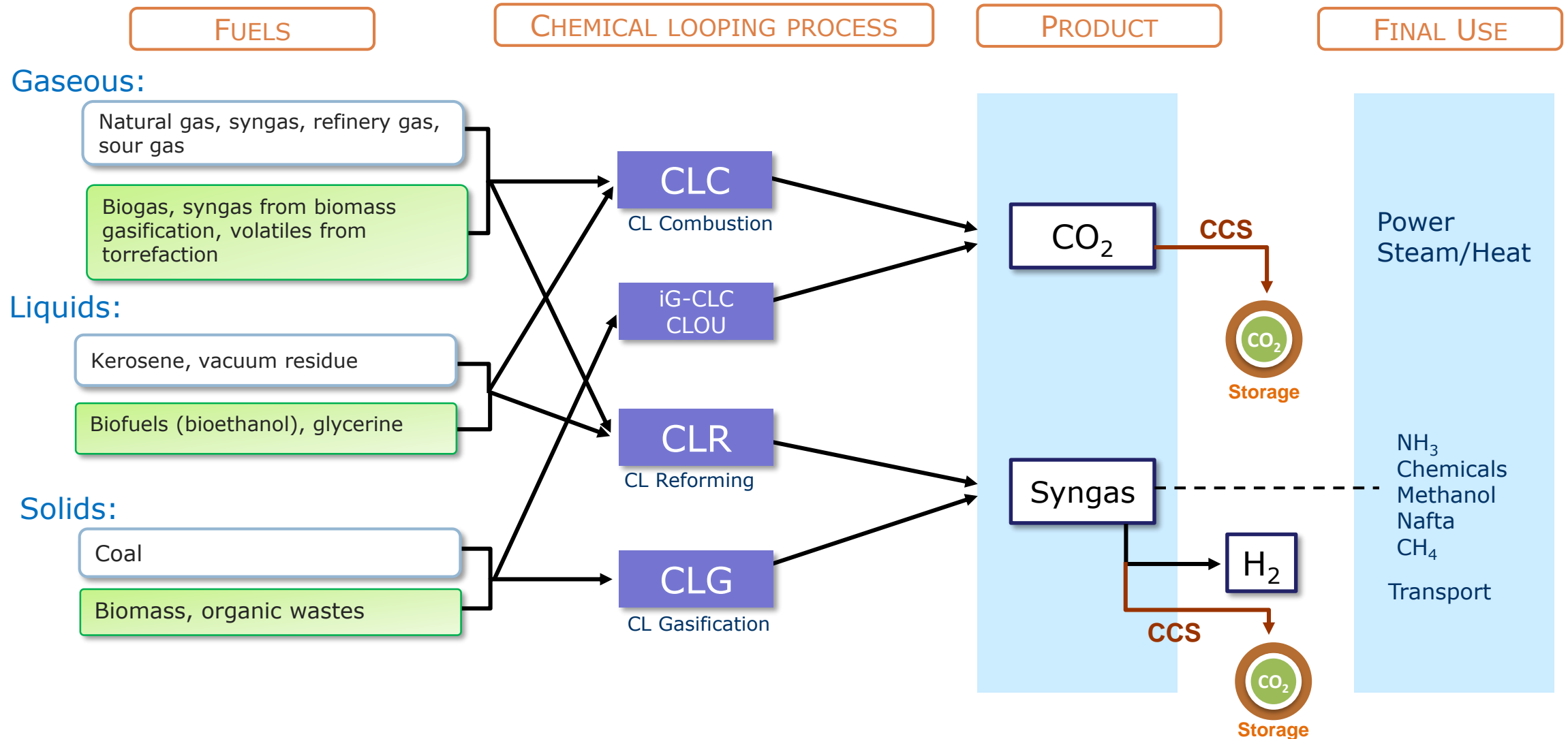
$\Delta H_r < 0$   $T_{FR}$  increases. Solids circulation rate no limited by the heat balance

$\Delta H_r > 0$   $T_{FR}$  drops. To avoid a large T drop, high  $G_s$  is desired.

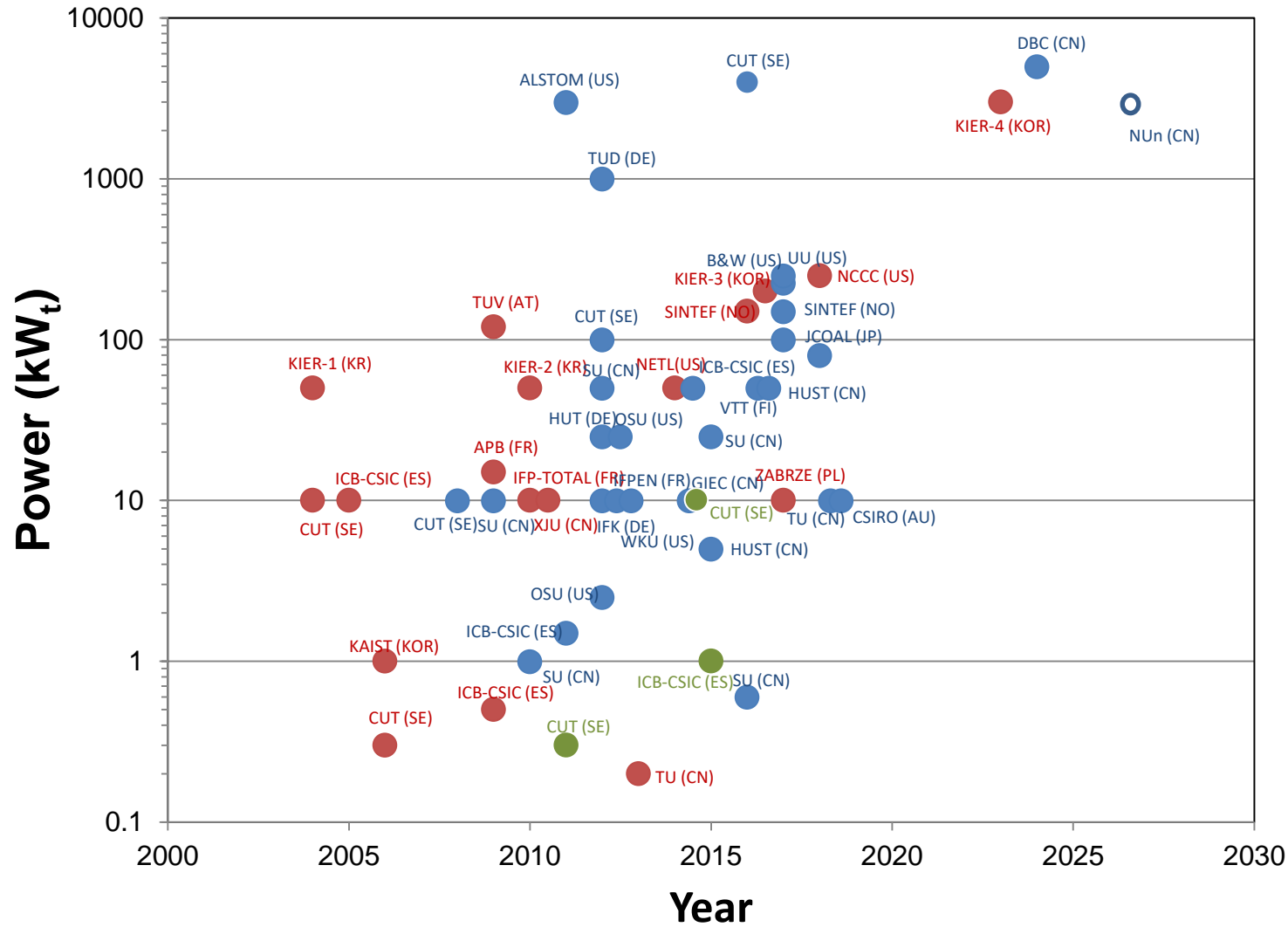
**Solids inventories** must be high enough to fully convert the fuel. (enough residence time in the FR, enough OC reactivity and good contact between oxygen carrier-fuel).

Linked to solids circulation rate to supply the oxygen.





# CHEMICAL LOOPING CONTINUOUS UNITS



- Gaseous
- Liquids
- Solids

+50 Chemical Looping units

Scale-up to 5 MW

+ 15000 h operational experience

# CHEMICAL LOOPING CONTINUOUS UNITS

## BFB-BFB

## BFB-CFB

## CFB-CFB

## MB-MB<sup>(1)</sup>/MB-EB

## SB-CFB

### Gaseous fuels

0.2	TU	10	CUT	1	KAIST	250	NCCC <sup>(1)</sup>		
0.3	CUT	10	XJU	10	ZABRZE				
0.5	ICB-CSIC	15	APB	120	TUV				
10	ICB-CSIC	50	KIER 1	150	SINTEF				
50	KIER 2	50	NETL	200	KIER 3				
<u>BFB-BFB-BFB</u>		3000	KIER 4						
10	IFPEN								

### Solid fuels

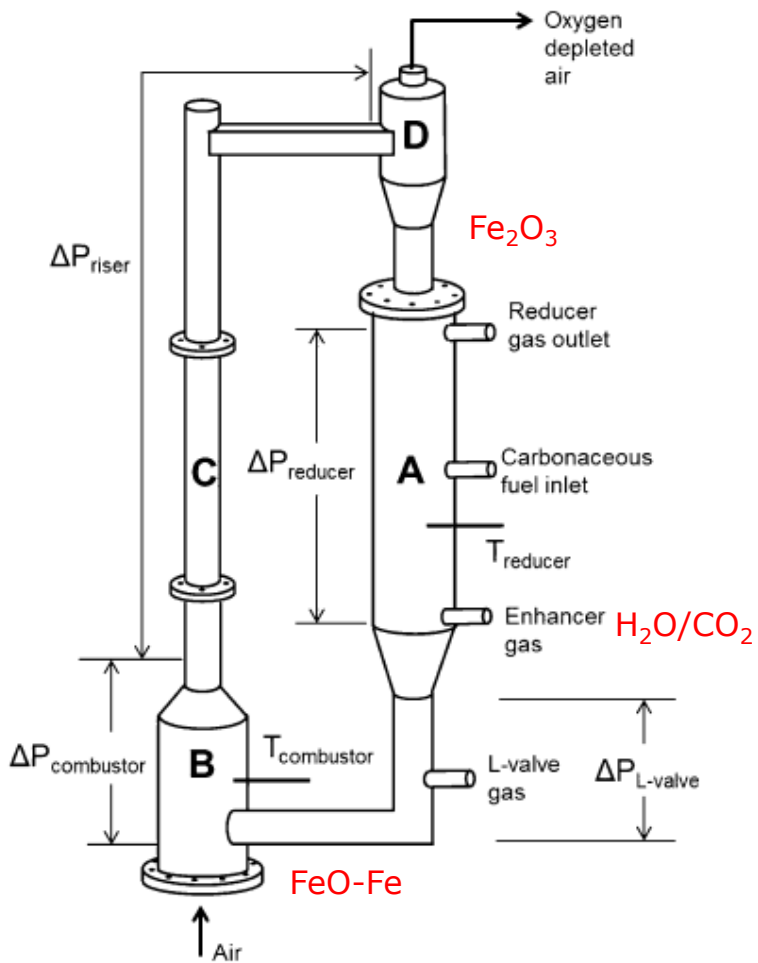
1.5	ICB-CSIC	0.6	SU	5	HUST	2.5	OSU	1	SU
		10	CUT	10	IFK	25	OSU	10	SU
<u>BFB-BFB-BFB</u>		10	WKU	50	SU	250	B&W		
10	IFPEN	10	GIEC	50	ICB-CSIC				
		10	TU	50	HUST				
		25	SU	80	TUV				
		50	VTT	100	CUT				
		4000	CUT	100	JCOAL				
		<u>2-step BFB -CFB</u>		150	SINTEF				
		25	HUT	225	UU				
				1000	TUD				
				3000	Alstom				
				3000	Nun				
				5000	DBC				

### Liquid fuels

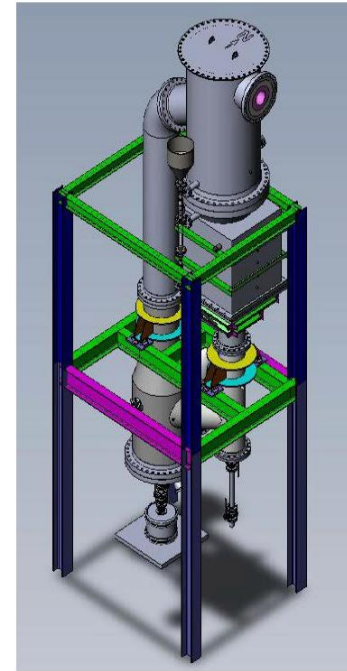
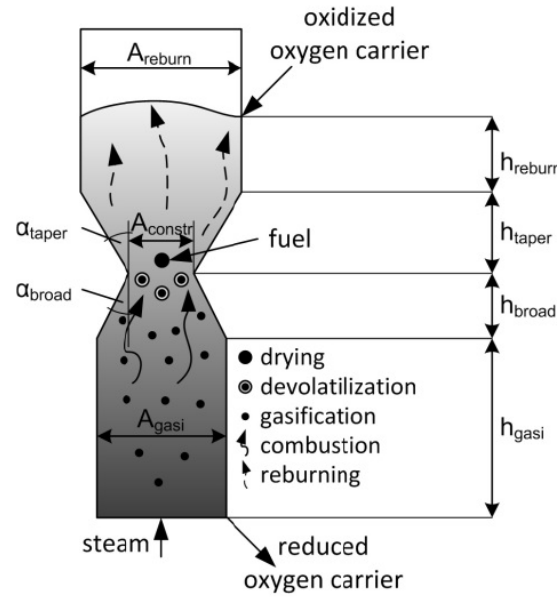
0.3	CUT	10	CUT
1	ICB-CSIC		

BFB = bubbling fluidized bed; CFB= circulating fluidized Bed; SB= spouted bed; MB= moving bed; EB= entrained bed; TFB= turbulent fluidized bed

250 kW B&W



Fuel reactor



- Thermal power: 250 kW<sub>th</sub>
- Coal size: Pulverized coal
- Max operating Temperature: 1100 °C
- Oxygen carrier: Iron based
- Reducer: Counter-current moving bed
- Combustor: bubbling bed
- Particle transport: Pneumatic
- Control solids circulation rate: L-valve
- Size: 1.5 mm

- ✓ Greater control of solids residence time and conversion
- ✓ Greater conversion of the fuel (+90%) and oxygen carrier
- ✓ High CO<sub>2</sub> purity (+99.5 vol%)
- ✓ Possibility to operate at pressure

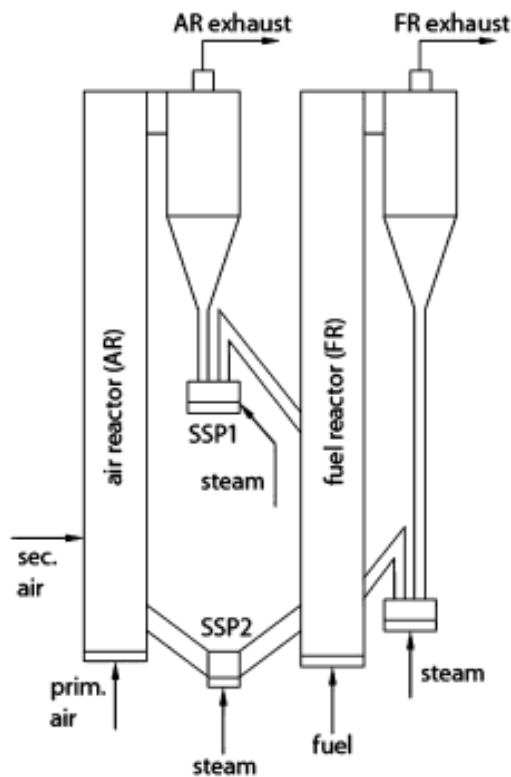
✗ High consume power to entrain big particles



120 kW

CFB-CFB

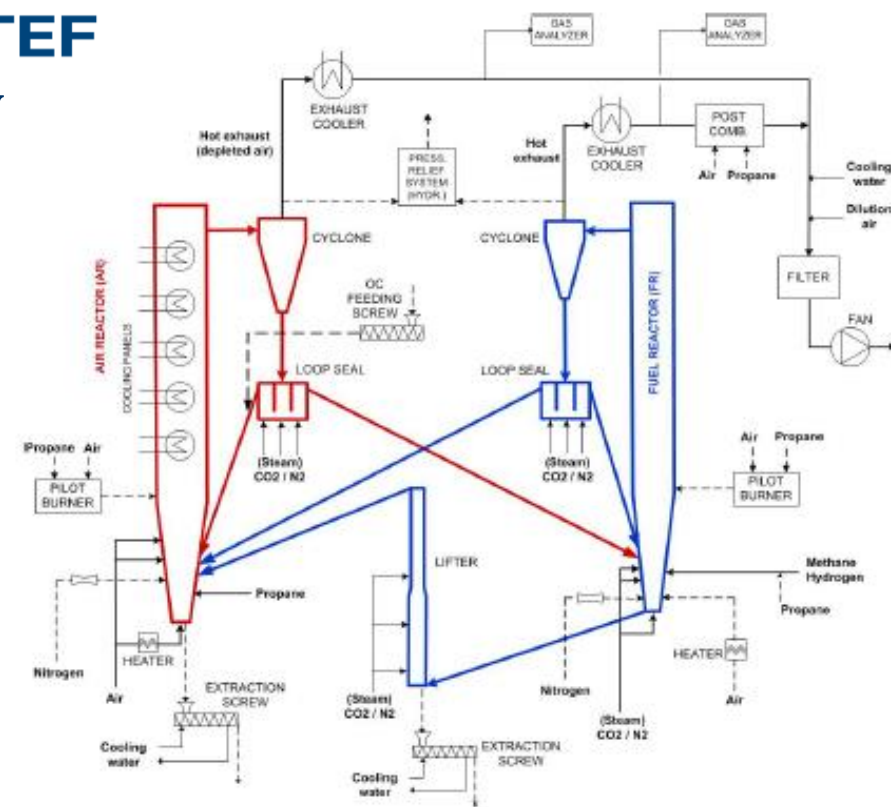
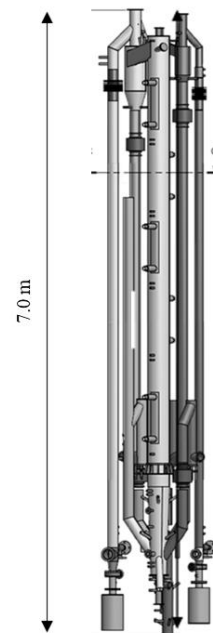
FR- turbulent  
AR- fast FB



- Hydraulic link at the bottom allows unit stabilization.
- Solids circulation rate depends on the AR fluidization.
- High solids circulation with low solids inventory (low  $t_r$  in FR/AR).
- Valid for scale-up. Similar to commercial power plants.



150 kW



- 2 CFB connected by 2 LS and lifter to transfer solids
- Solids residence time independent in FR and AR.
- Temperature control by temperature of hot air in AR and 5 air cooled heat exchangers
- Several screwfeeders to control solid inventories



10 kW

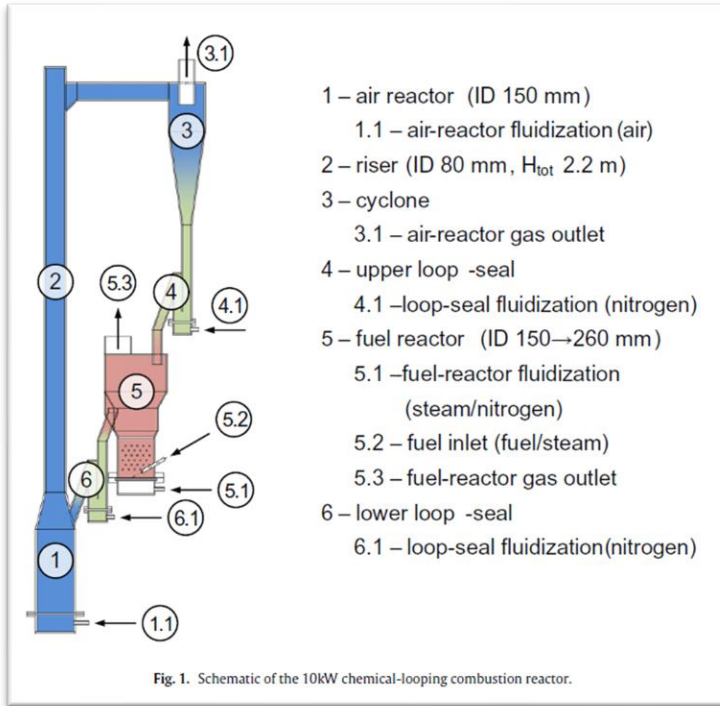


Fig. 1. Schematic of the 10kW chemical-looping combustion reactor.

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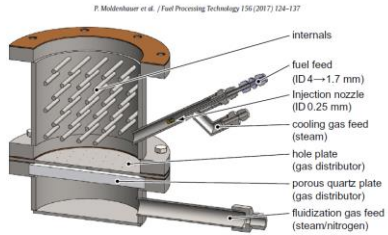


Fig. 2. Lower section of the fuel reactor for direct injection of liquid fuel. During operation, this section is completely filled with fluidized oxygen-carrier particles.

**Oxygen carriers:**  
 Ilmenite  
 Calcium manganate

**Fuels:**  
 Sulphur-free kerosene  
 Sulphurous kerosene  
 Fuel oil 1  
 Vacuum residue

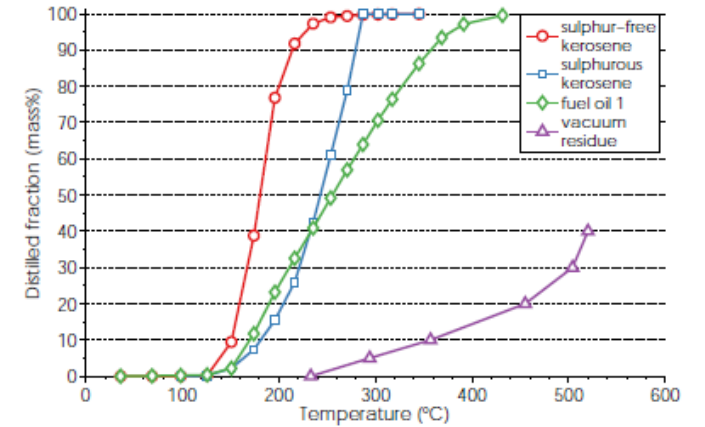
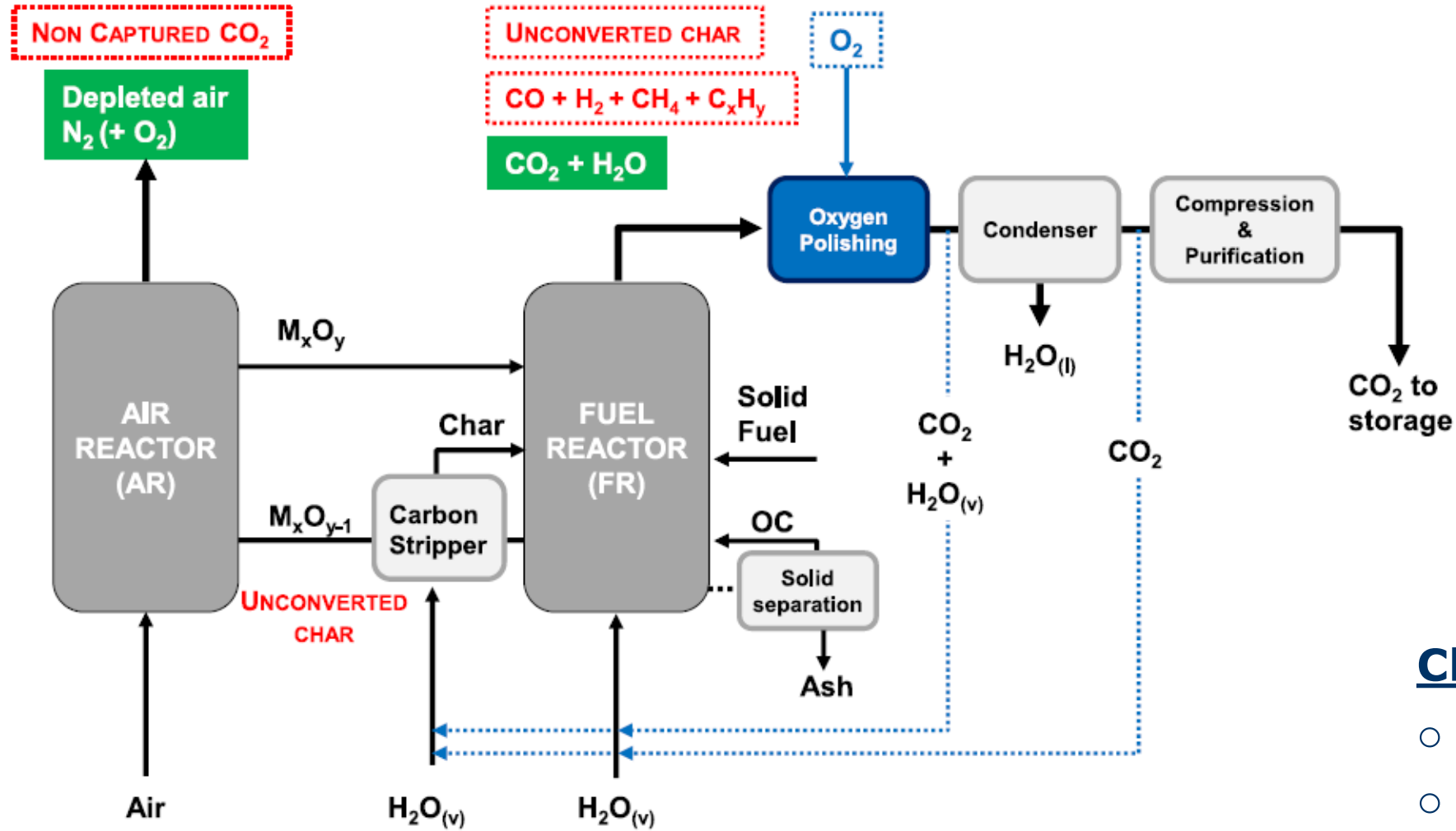


Figure 2.3: Boiling range distribution of the different liquid fuels used: sulphur-free kerosene, sulphurous kerosene, fuel oil 1 and vacuum residue.<sup>2</sup>

- Problems with feeding. Heavy liquid blends were used.
- No agglomeration.
- 67 h operation (900-1050 °C)
- fuel could be oxidized to about 87%, and up to 88% of all carbon leaving the FR was CO<sub>2</sub>.

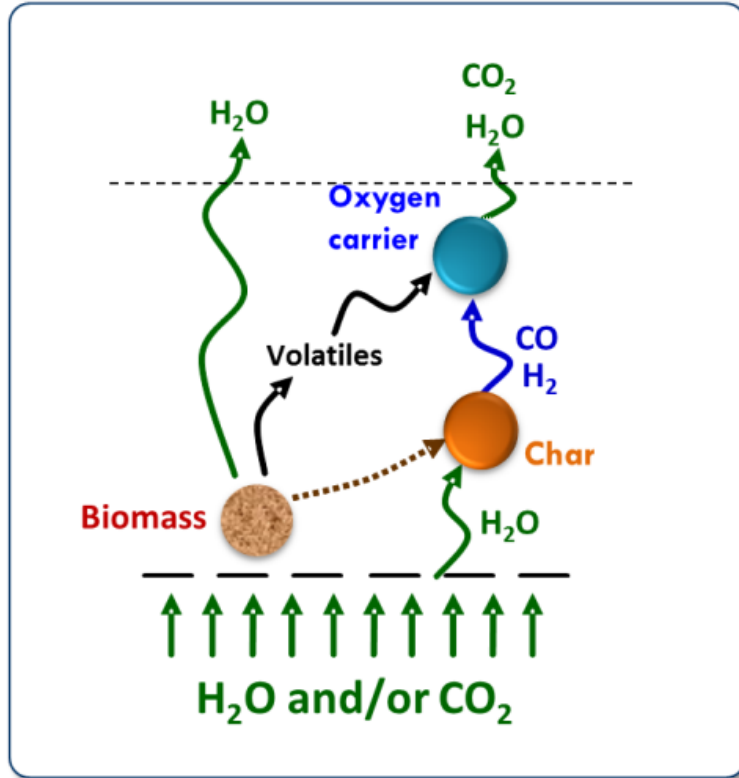


## Challenges

- $CO_2$  capture
- Oxygen demand

In situ Gasification- CLC

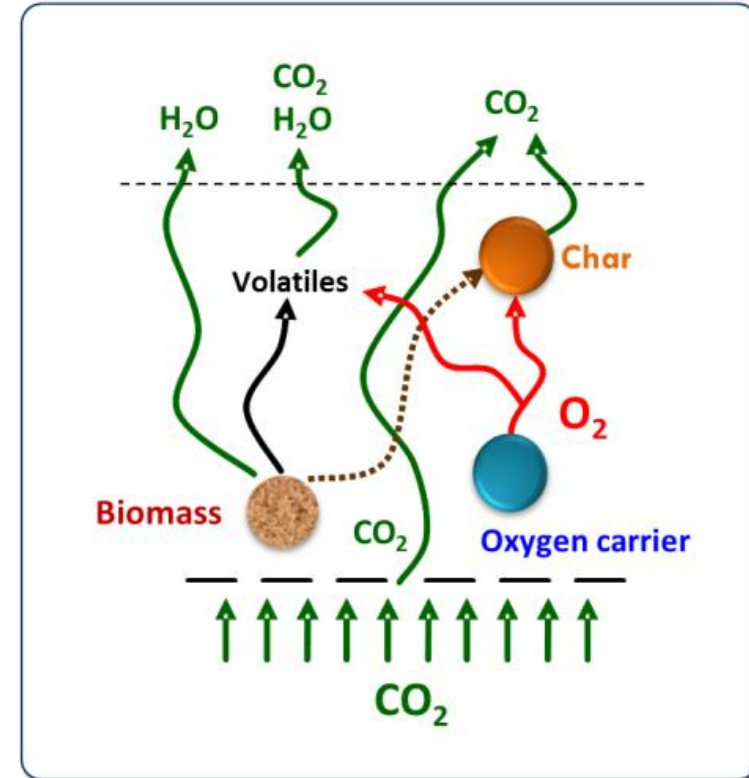
*iG- CLC*



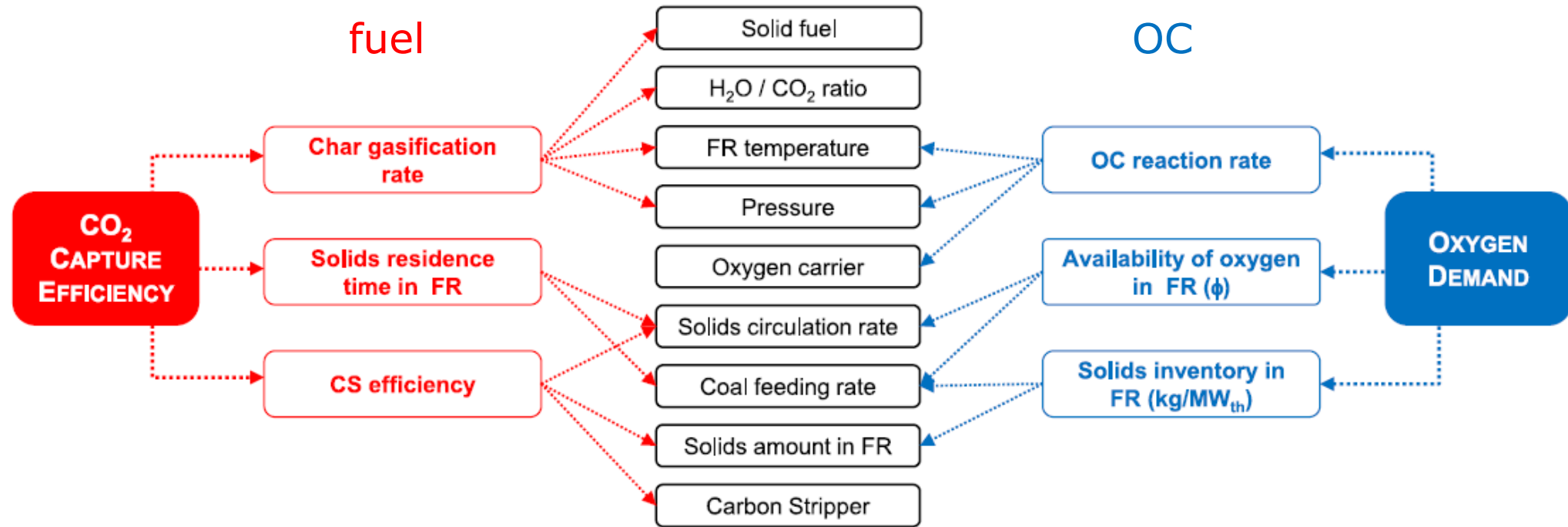
- Low cost oxygen carriers
- Unburnt products need improvements

Chemical Looping with Oxygen Uncoupling

*CLOU*



- Synthetic oxygen carriers
- High capture and combustion efficiency
- Longer OC lifetime is needed



### Main operational variables

- Temperature
- Oxygen-to-fuel ratio ( $\phi$ ),
- Solids inventory in FR

### Main design solutions

- Carbon Stripper
- FR design

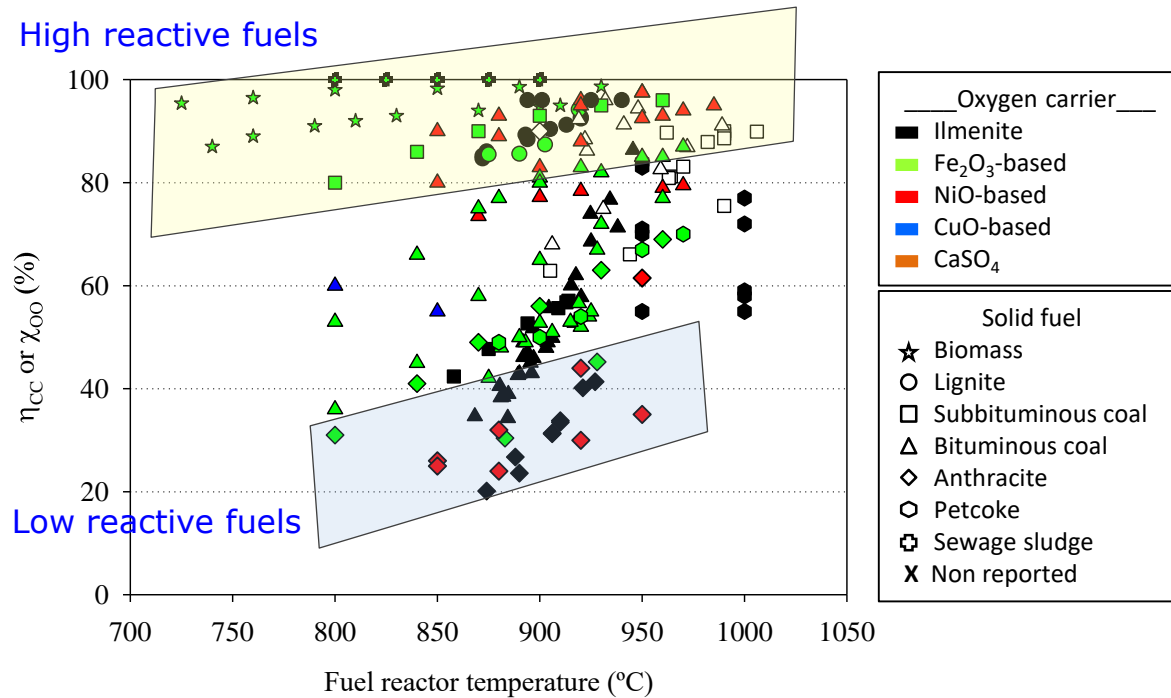
Table 4

Experimental conditions for CO<sub>2</sub> capture efficiency and oxygen demand from different iG-CLC continuous units.

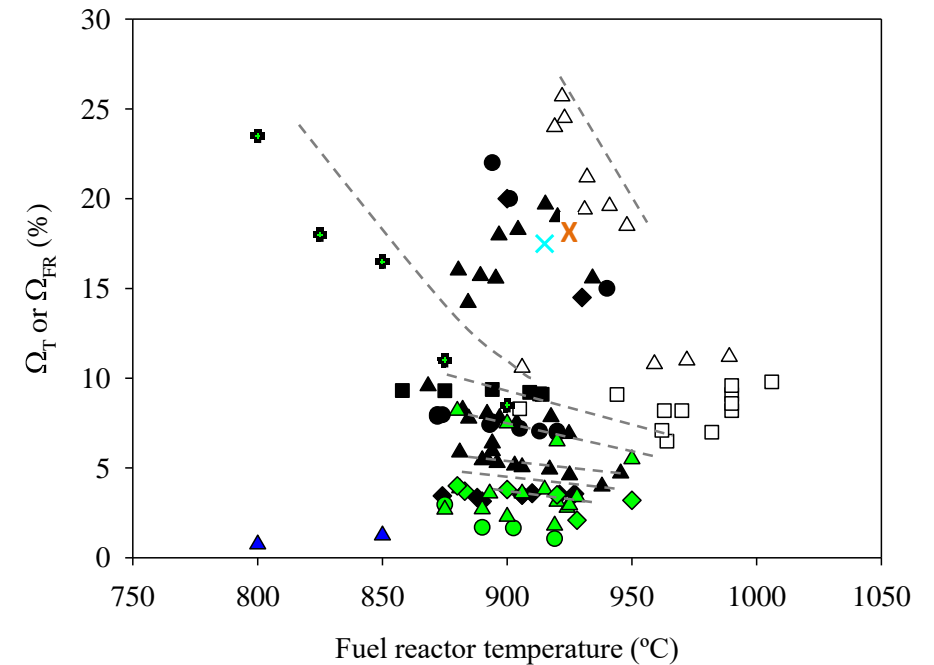
No.	Name	Nominal power (kW)	OC	Fuel	FR design	T (°C)	$\phi$	$m_{OC}$ (kg/MW <sub>th</sub> )	$X_{O_2}$ (%)	CO <sub>2</sub> capture		Oxygen demand		Ref.
										$\eta_{CC}$ (%)	$\chi_{OO}$ (%)	$\Omega_{FR}$ (%)	$\Omega_T$ (%)	
1	CUT	10	Ilmenite	Bit. Coal	Bubbling	950	0.5–2.2	1850–2940	50–80	82.5–96	83–93	16–22	n.a.	[36]
2	CUT	10	Ilmenite	Petcoke	Bubbling	950	0.4–1	1030	66–78	60–75	n.a.	~25	n.a.	[37]
3	CUT	10	Ilmenite	Petcoke	Bubbling	950–1000	0.5–1.5	1117	55–75	68–87	n.a.	27–36	n.a.	[118]
4	CUT	10	Ilmenite + CaCO <sub>3</sub>	Petcoke	Bubbling	950–1000	0.7–2.5	1430	41–81	58–86	64–81	24–33	n.a.	[114]
5	CUT	10 <sup>a</sup>	Ilmenite	Bit. Coal	Bubbling	970	1.5–8	2000	54–56	90–95	88–92	23	n.a.	[115]
6	CUT	10 <sup>a</sup>	Ilmenite	Petcoke	Bubbling	970–1000	0.5–3.8	1364	45–65	51–87	61–83	18–21	n.a.	[115]
7	CUT	10 <sup>a</sup>	Mn ore	Petcoke	Bubbling	970	1–3.7	1500	60–69	89–98	91–97	11–14	n.a.	[115]
8	CUT	100	Ilmenite	Bit. Coal	High vel.	940–980	1–5	200–770	52–67	n.a.	96–99.5	16–25	n.a.	[120,123]
9	CUT	100	Ilmenite	Wood char	High vel.	929–973	1–6	300–850	54–89	n.a.	91–97	4.7–15.5	n.a.	[121]
10	CUT	100	Ilmenite + Mn ore	Bit. Coal	High vel.	935–971	0.5–3	370–1300	54–77	n.a.	98–99	8.5–18.5	n.a.	[122]
11	CUT	100	Iron ore	Bit. Coal	High vel.	945	1.5	480–650	n.a.	n.a.	92–98	13–19	n.a.	[100]
12	SU	1	Iron ore	Biomass	Spouted	720–930	n.a.	n.a.	n.a.	95.5–98.5	~98	n.a.	n.a.	[127]
13	SU	1	Iron ore	Bit. Coal	Spouted	880–970	n.a.	970	92	77–87	n.a.	5.5–8.2	n.a.	[129]
14	SU	1	Iron ore	Anthracite	Spouted	880–970	n.a.	750	66–82	49–70	n.a.	3.2–4	n.a.	[129]
15	SU	1	Iron ore + K <sub>2</sub> CO <sub>3</sub>	Anthracite	Spouted	900–975	n.a.	2130	n.a.	35–92.5	n.a.	n.a.	n.a.	[130]
16	SU	1	Hematite	Sewage s.	Spouted	800–900	n.a.	7200	82–91	~100	n.a.	n.a.	8.5–23.5	[132]
17	SU	1	Hematite	Bit. coals	Spouted	800–960	n.a.	900–1000	56–91	36–96	n.a.	n.a.	n.a.	[133]
18	SU	50	Fe <sub>2</sub> O <sub>3</sub>	Bit. Coal	High vel.	950	0.24	50–100	>85	83–87	n.a.	2–6.5	n.a.	[135]
19	ICB-CSIC	0.5	Ilmenite	Bit. Coal	Bubbling	870–950	1.1	3140	95	35–86	n.a.	5–15	5–10	[136]
20	ICB-CSIC	0.5	Ilmenite	Bit. Coal	Bubbling	890	0.5–8.4	1500–3900	80–95	38–74	n.a.	14–36	8–15	[138]
21	ICB-CSIC	0.5	Ilmenite	Bit. Coal	Bubbling	850–920	1.0	1380	77	41–55	n.a.	~25	~9.5	[137]
22	ICB-CSIC	0.5	Ilmenite	Lignite	Bubbling	870–920	1.2	1770	89	82–93	n.a.	29–31	7–8	[137]
23	ICB-CSIC	0.5	Ilmenite	Anthracite	Bubbling	870–930	1.0	1400	87	20–40	n.a.	~16	~3.5	[137]
24	ICB-CSIC	0.5	Fe-ESF	Bit. Coal	Bubbling	880–930	1–6	2850–3500	89	44.5–67	n.a.	6.8–13.5	3.2–6.7	[140]
25	ICB-CSIC	0.5	Fe-ESF	Anthracite	Bubbling	875–930	1.0	2070	88	8–20	n.a.	5.7–21.2	1–1.5	[198]
26	ICB-CSIC	0.5	Iron ore	Bit. Coal	Bubbling	875–920	1.2	1463	87	40–55	n.a.	5.9–10.4	1.8–2.7	[101]
27	ICB-CSIC	0.5	Iron ore	Lignite	Bubbling	875–920	1.0	2023	87	85.5–94	n.a.	10.7–15	1.1–2.9	[101]
28	ICB-CSIC	0.5	Iron ore	Anthracite	Bubbling	880–930	1.0	2847	70	31–45	n.a.	7–17	2.1–3.7	[101]
29	ICB-CSIC	0.5	Iron ore	Biomass	Bubbling	880–980	1–4	600–1550	85–90	90–100	n.a.	7–34.6	3.4–29.9	[139,141]
30	ICB-CSIC	0.5	Fe-Mn	Bit.-Sub-Bit	Bubbling	900	1–1.5	1275–1750	97	74–95.5	n.a.	2.9–3.8	2.8–4.4	[79,89]
31	ICB-CSIC	50	Ilmenite	Bit. Coal	High vel.	905–1006	1.1–1.5	253–680	80–94	61–90	n.a.	8–14	6.5–9.8	[144,145]
32	TUHH	25	Ilmenite	Lignite	2 reactors	900–940	16–55	4505 <sup>b</sup>	92	96–98	n.a.	11–25	10–24	[148]
33	TUHH	25	CuO	Bit. Coal	2 reactors	800–850	n.a.	n.a.	92–99	35–63	45–64	0.25–1.25	n.a.	[149]
34	OSU	25	Fe <sub>2</sub> O <sub>3</sub>	Sub-Bit.	Moving	900–1000	n.a.	n.a.	n.a.	94–95	94–96	0.1–1.3	n.a.	[153]
35	HUST	5	Hematite	Bit. Coal	Bubbling	900–1000	n.a.	417–1250	n.a.	40–85	n.a.	3.7–26.5	n.a.	[156]
36	Alstom Power	3000	CaSO <sub>4</sub>	Coal+CaCO <sub>3</sub>	High vel.	900–930	n.a.	n.a.	n.a.	n.a.	n.a.	15–20	n.a.	[163]
37	TUD	1000	Ilmenite	Bit. Coal	High vel.	930	1	156	n.a.	n.a.	n.a.	12–17 <sup>c</sup>	n.a.	[42]
38	TUD	1000	Ilmenite	Anthracite	High vel.	900	1.6	100	50	90	n.a.	20	n.a.	[159]

<sup>a</sup> In-bed coal feeding.<sup>b</sup> Solids inventory per fuel reactor stage.<sup>c</sup> Fuel reactor was fluidized with a mixture of air and steam.

## Carbon capture efficiency



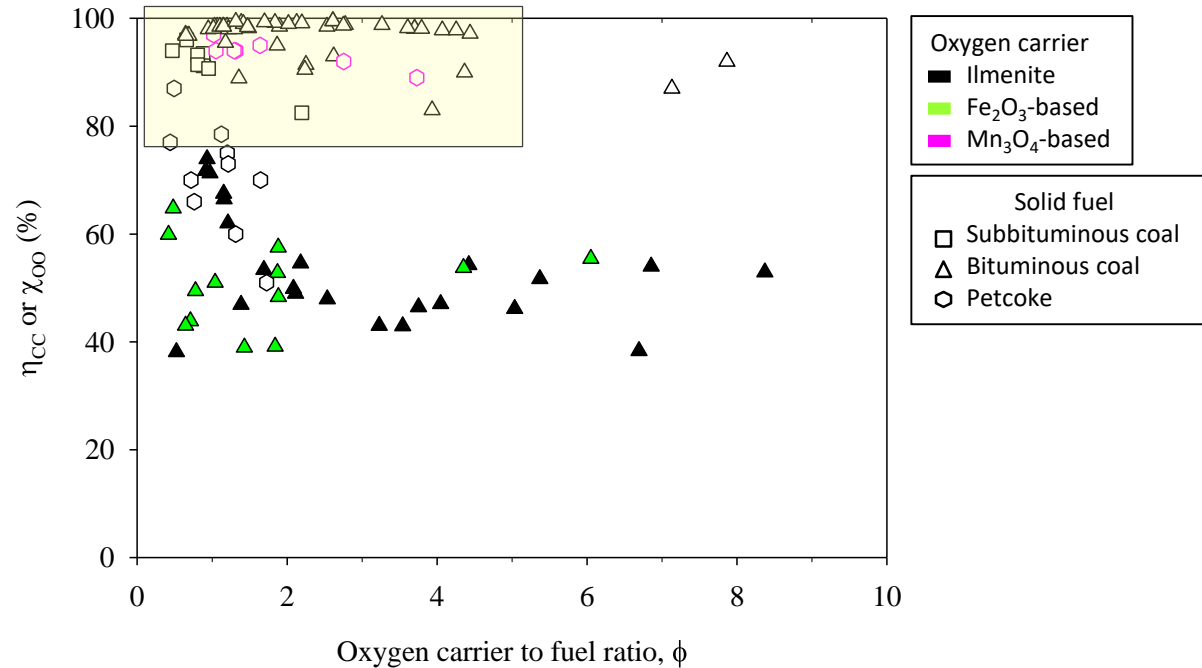
## Oxygen demand



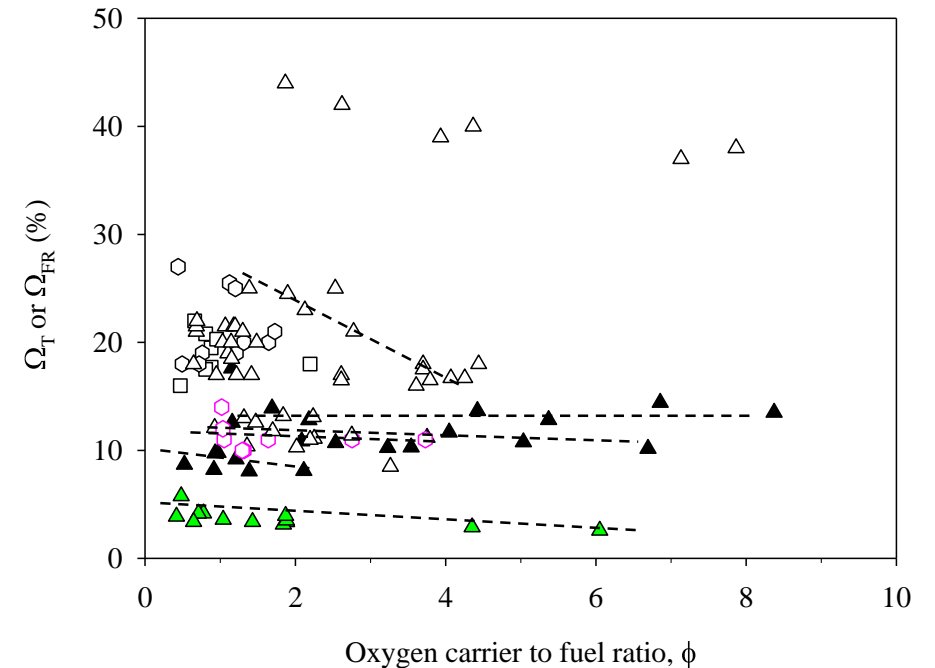
- Higher Temperatures produces higher CO<sub>2</sub> capture efficiency and lower oxygen demand for all OCs and fuels. (through increase OC reactivity but especially in char gasification rate, the limiting step in iG-CLC).
- Temperatures of 1000 °C produces Carbon Captures nearly 100%
- Oxygen demands form 2 to 25 can be found

Symbols: Open=with CS, Closed=without CS.

## Carbon capture efficiency



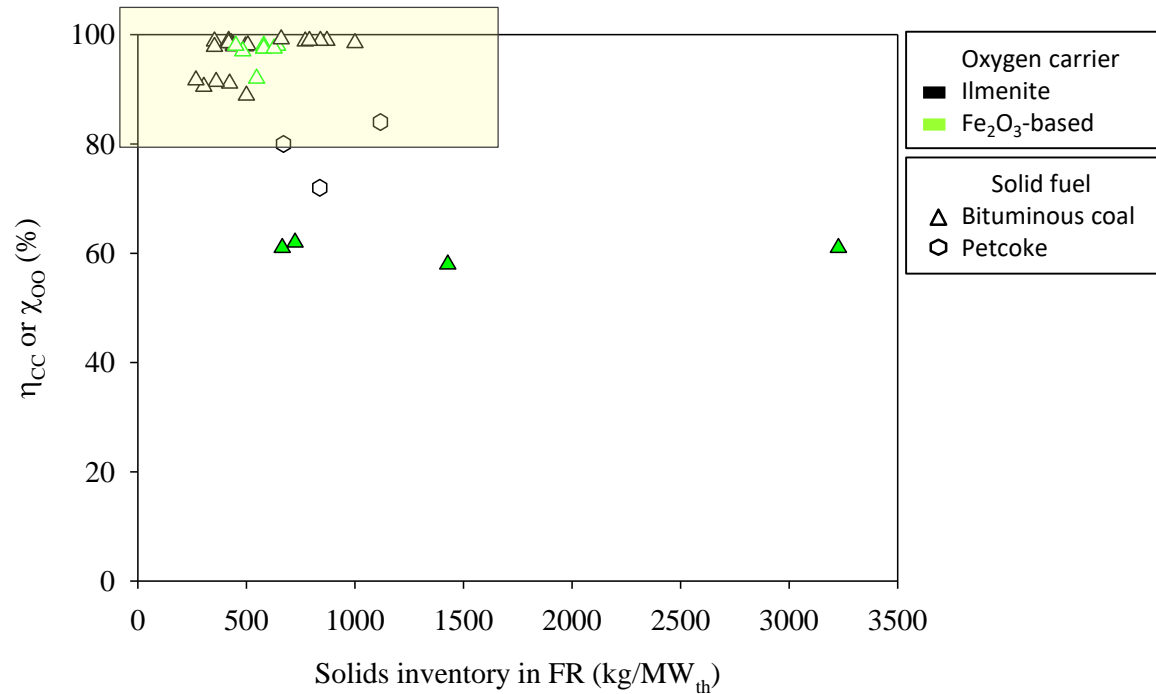
## Oxygen demand



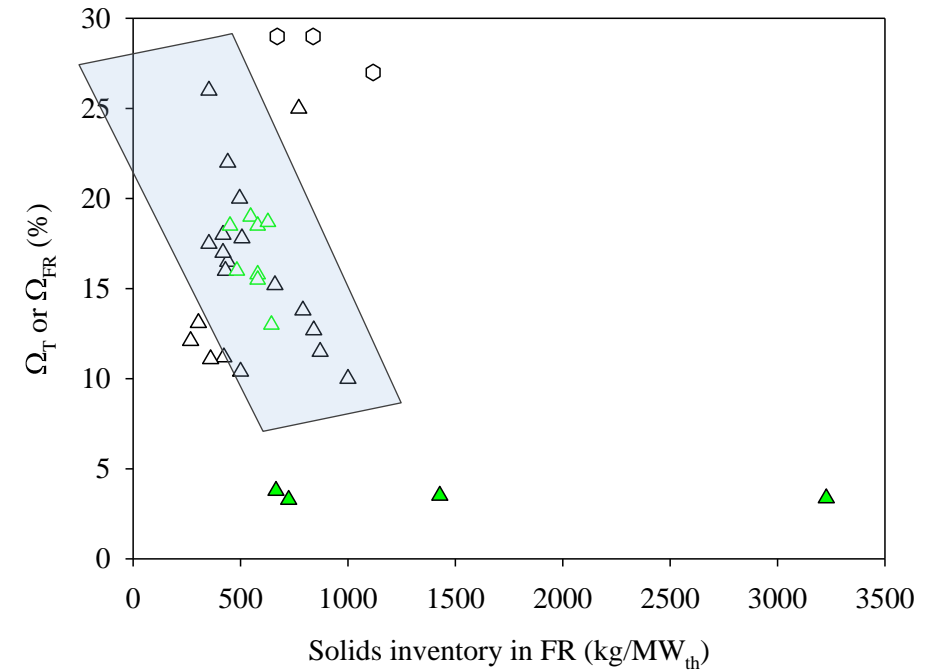
- The relevance of the Carbon Stripper (CS) is demonstrated
- **Without CS**, higher  $\phi$  leads to lower CO<sub>2</sub> capture efficiency (through  $t_r$  and char gasification)
- **With CS**, CO<sub>2</sub> capture efficiency close to 100% are achieved.

Symbols: Open=with CS, Closed=without CS.

## Carbon capture efficiency

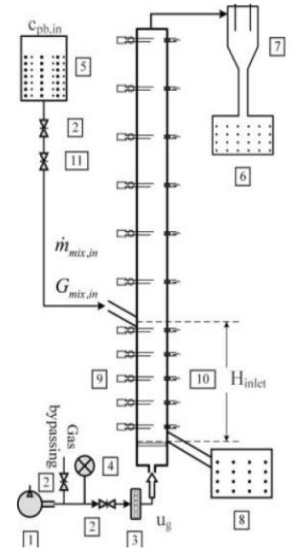
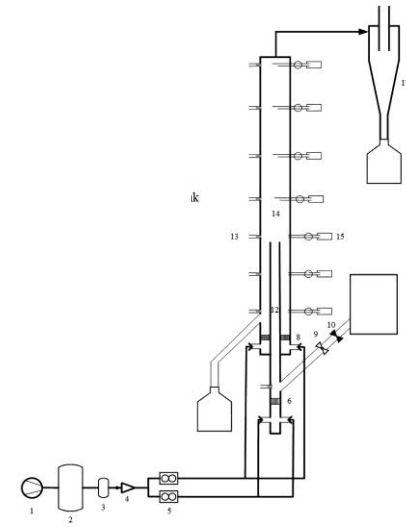
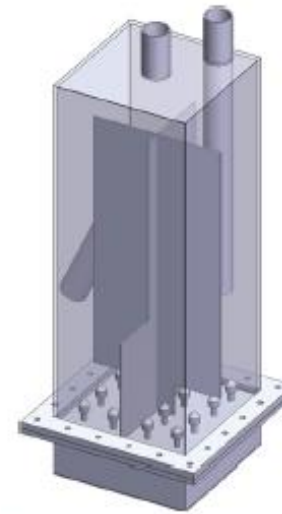
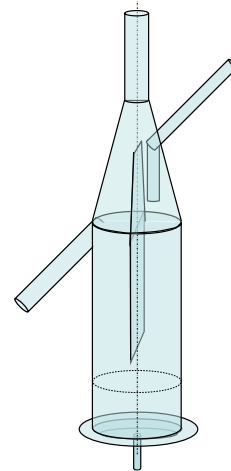
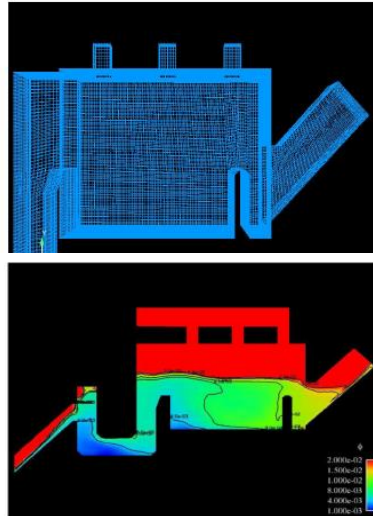
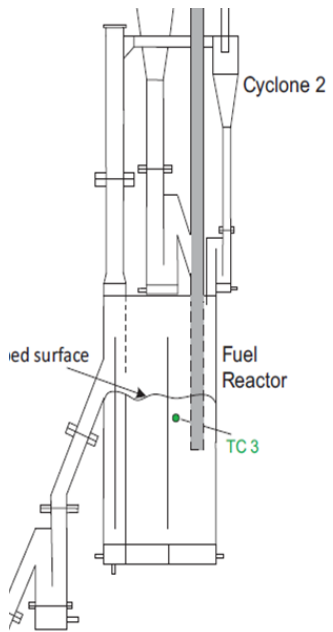


## Oxygen demand

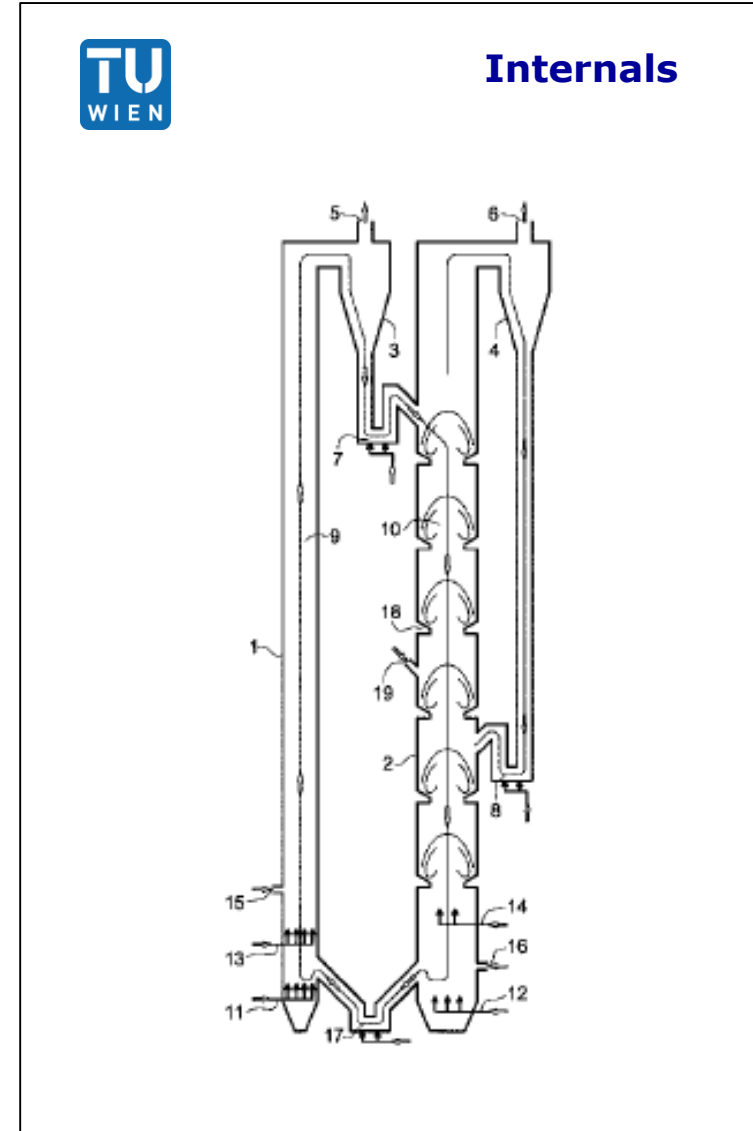
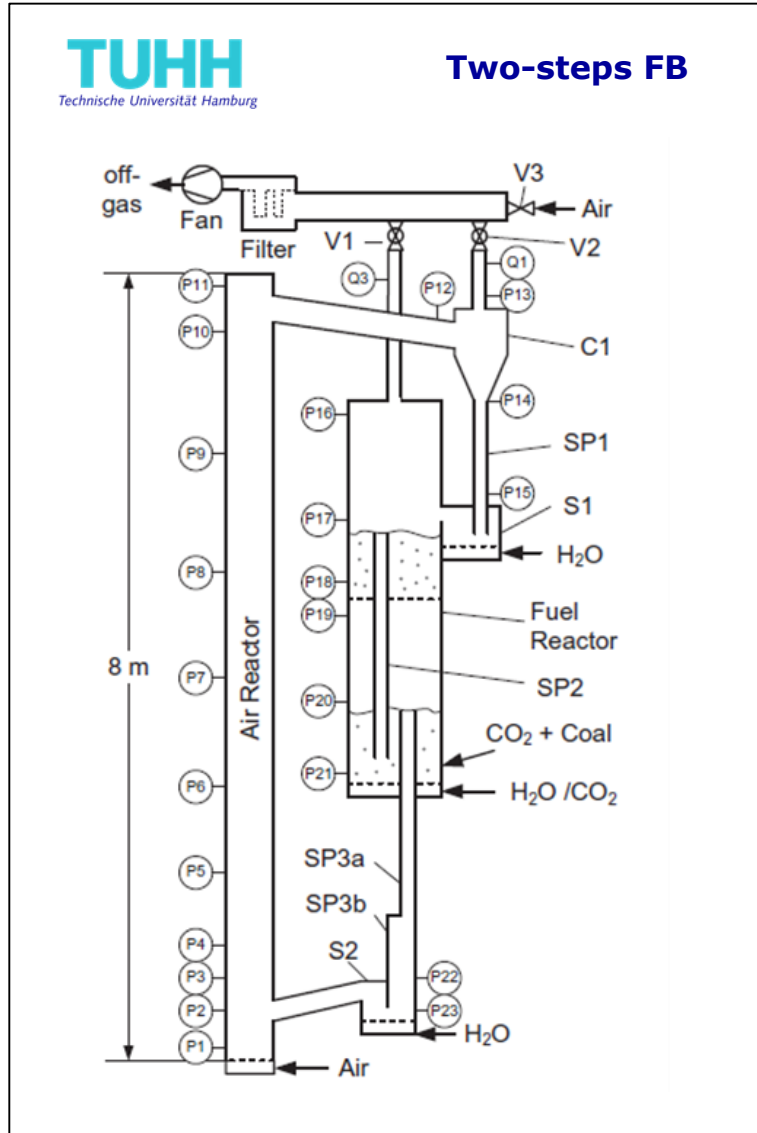


- **Oxygen demand** decrease from 300 to 700 kg/MW.
- Solid inventories above 1000 kg/MW are not recommended because of high pressure drop
- CO<sub>2</sub> capture is low dependent on solids inventory (Char is returned from CS)

Symbols: Open=with CS, Closed=without CS.

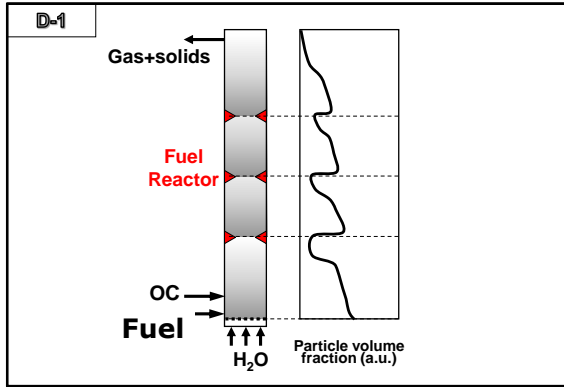


- |                        |          |
|------------------------|----------|
| A. CS integrated in FR | CUT      |
| B. One-chamber CS      | TUD      |
| C. Two-chamber CS      | ICB-CSIC |
| D. Four-chamber CS     | CUT      |
| E. Annular CS          | TU       |
| F. Riser-based CS      | TU       |

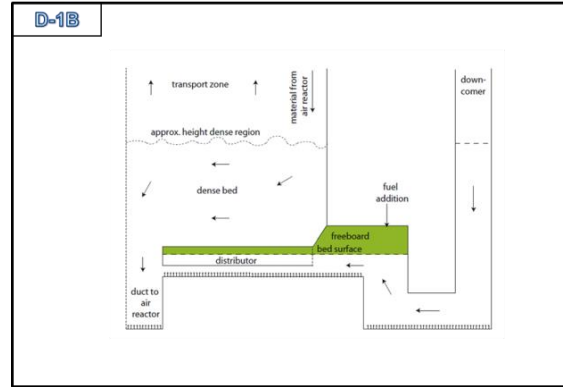




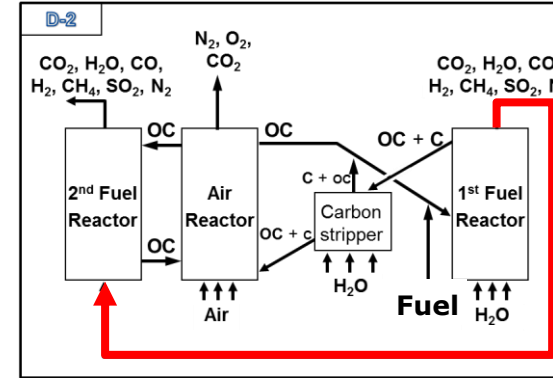
**Internals**  
Vienna UT (1)



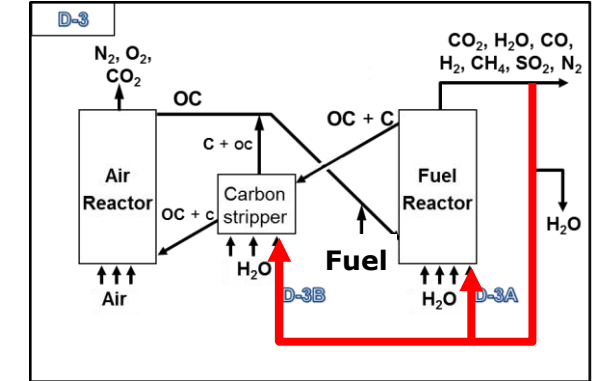
**Volatiles distributor**  
Chalmers UT



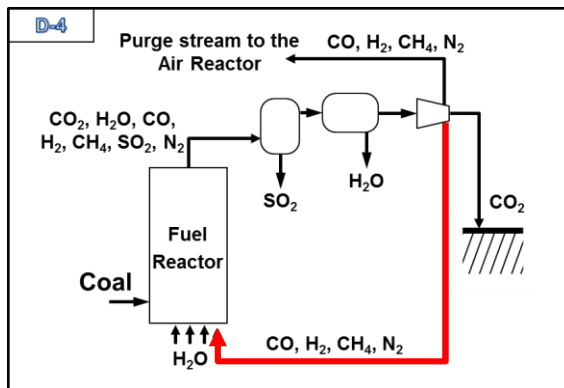
**Secondary FR**  
ICB-CSIC



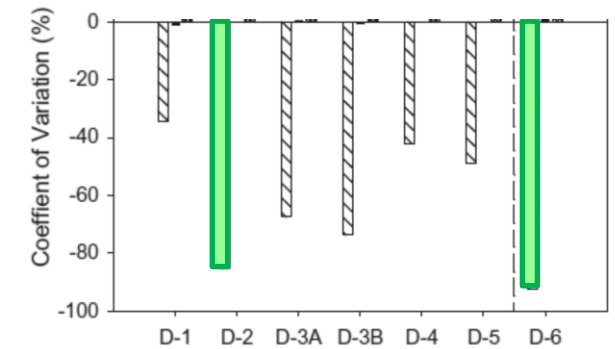
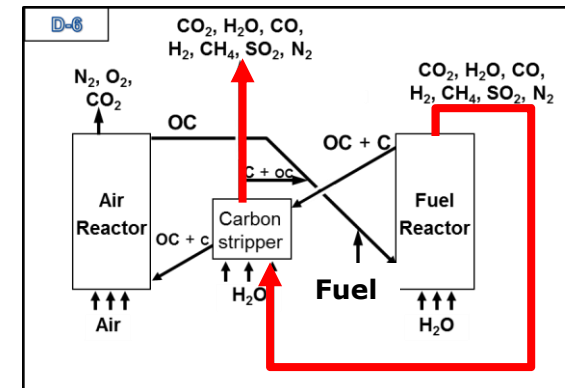
**Gas recirculation**  
Hamburg UT



**Fuel to CS**  
ICB-CSIC(2)



**Option 2 and 5**  
ICB-CSIC(2)



(1) Tested by ICB-CSIC with coal (Pérez-Vega et al., Fuel 2019;250:8-16)

(2) Tested by ICB-CSIC with coal (Abad et al., Fuel 2020;271:117514)



### TUDA 1 MW<sub>th</sub>

### CUT (12)-4 MW<sub>th</sub>

### CHEERS 5 MW<sub>th</sub>

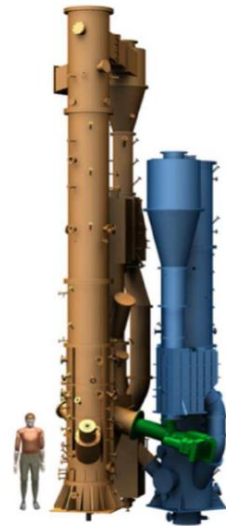
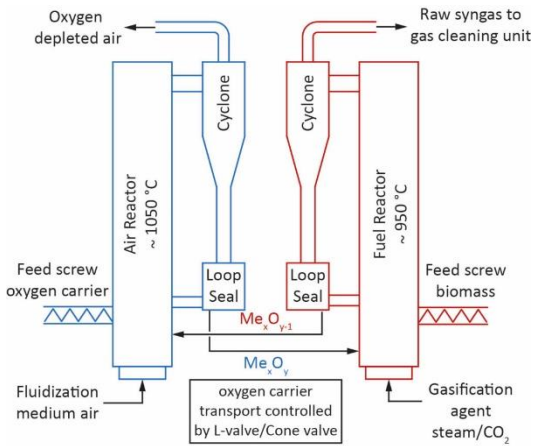
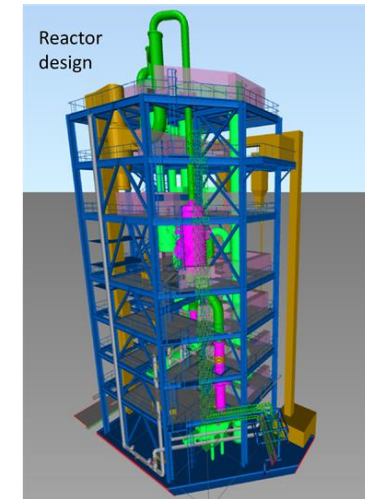
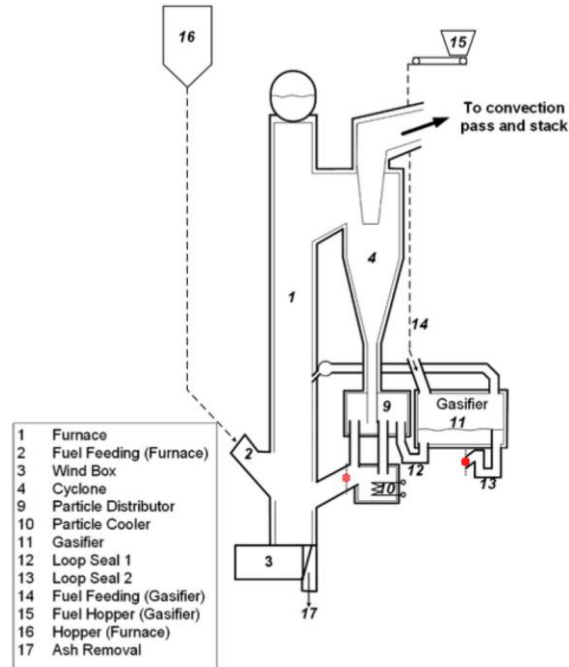


Figure 8 Drawing of TUDA 1 MW<sub>th</sub> pilot plant



Deyang, China

## TUDA 1 MW

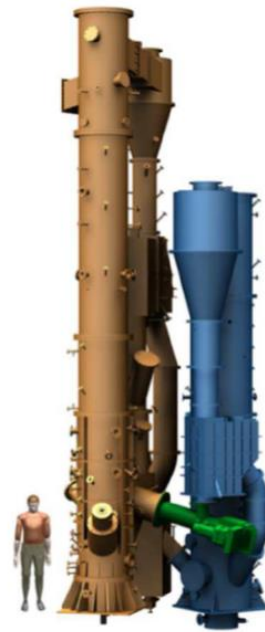
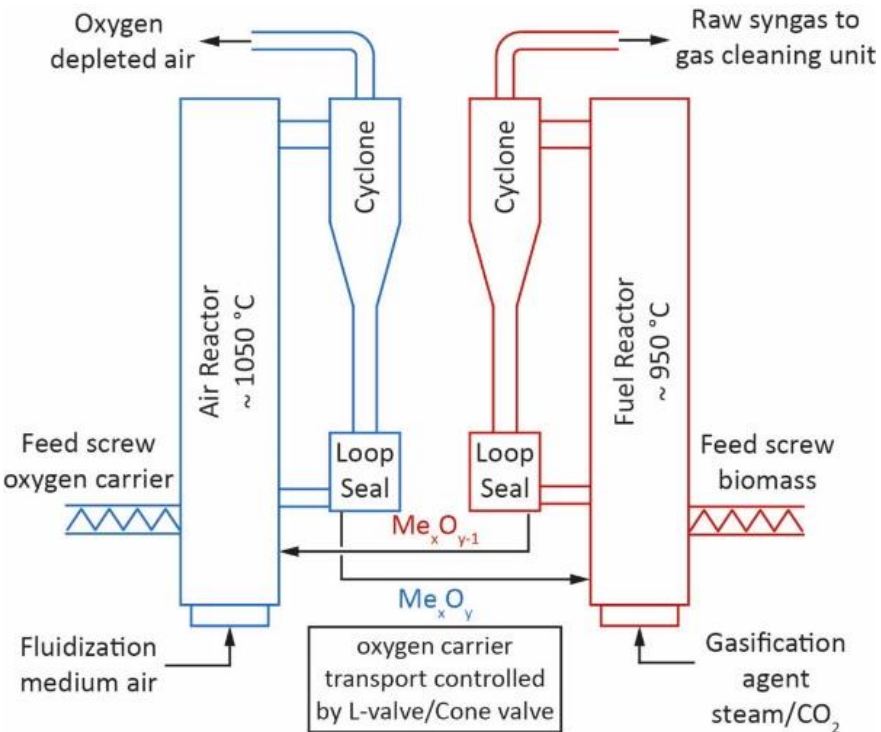
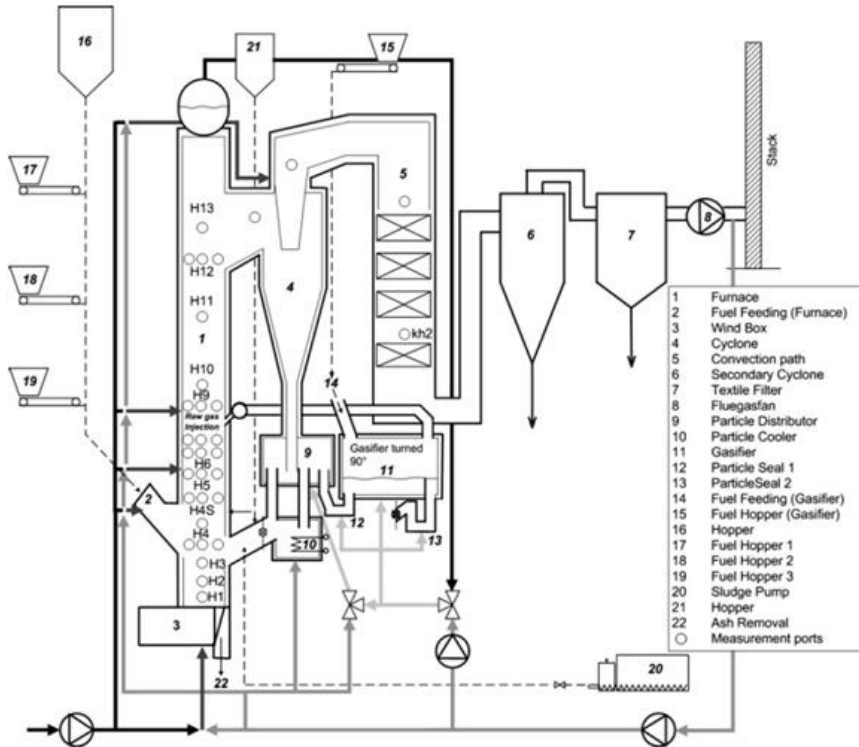


Figure 8 Drawing of TUDA 1 MW<sub>th</sub> pilot plant

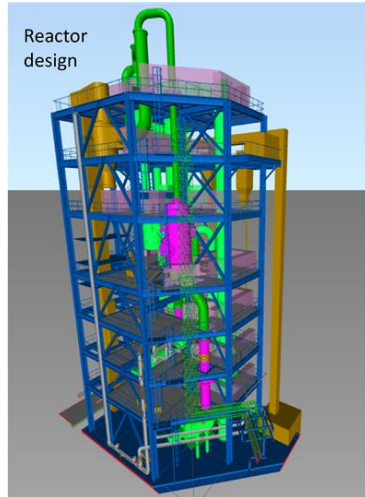
- CFB – CFB configuration
- Connected by L valves
- No Carbon stripper (now)
- Autothermal
- CLC, CLG
  
- Coal, biomass
- Ilmenite, iron ore
  
- $CO_2$  capture up to 90% (anthracite)
- Oxygen demands 12-17% (Bit.coal)



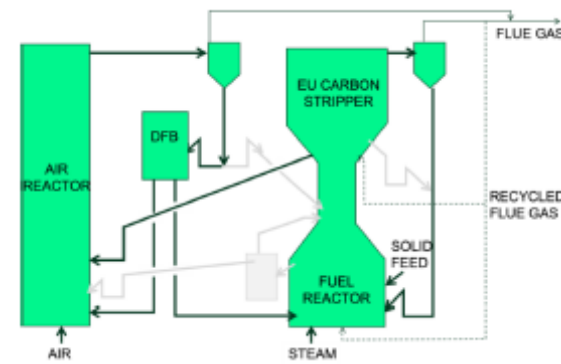
## CUT (12) 4 MW



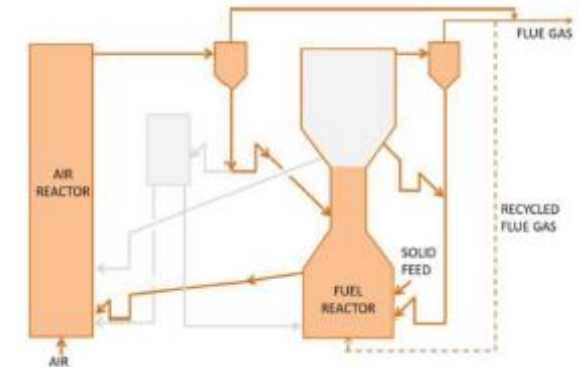
- 12 MW boiler for biomass combustion
- 4 MW gasifier adapted in the return loop to be used as a DFB
- Using OC as bed material, gasifier acts as FR and boiler as AR
- Segregation of char particles in FR lowered combustion efficiency
- No optimized for CL but very useful (OC-ash interaction)
- Long term experience
- Ilmenite, Mn ore
- Biomass

CHEERS 5 MW<sub>th</sub>

In March 2024, after 20 years of research and accumulation, the research team of Cai Ningsheng and Li Zhenshan in the Department of Energy achieved a major technological breakthrough in the cutting-edge research of **chemical looping combustion** and successfully realized the **self-heating continuous operation (70 h)** of a **5 MW<sub>th</sub> chemical looping combustion system for the first time in the world**. Deyang, China.



petcoke

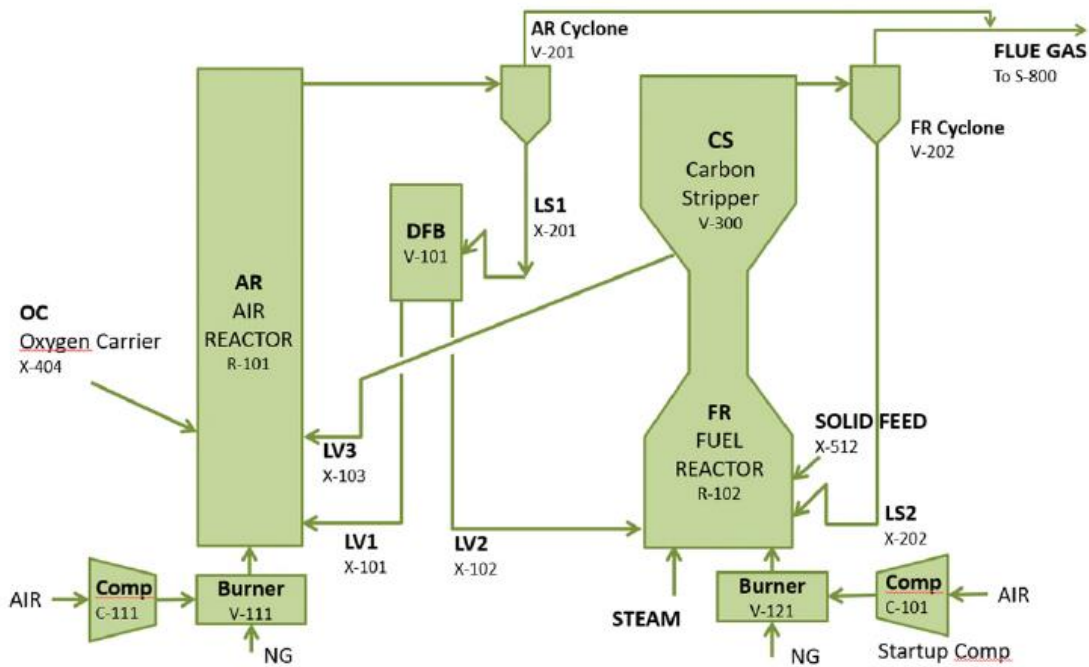


lignite

Oxygen carrier: ilmenite

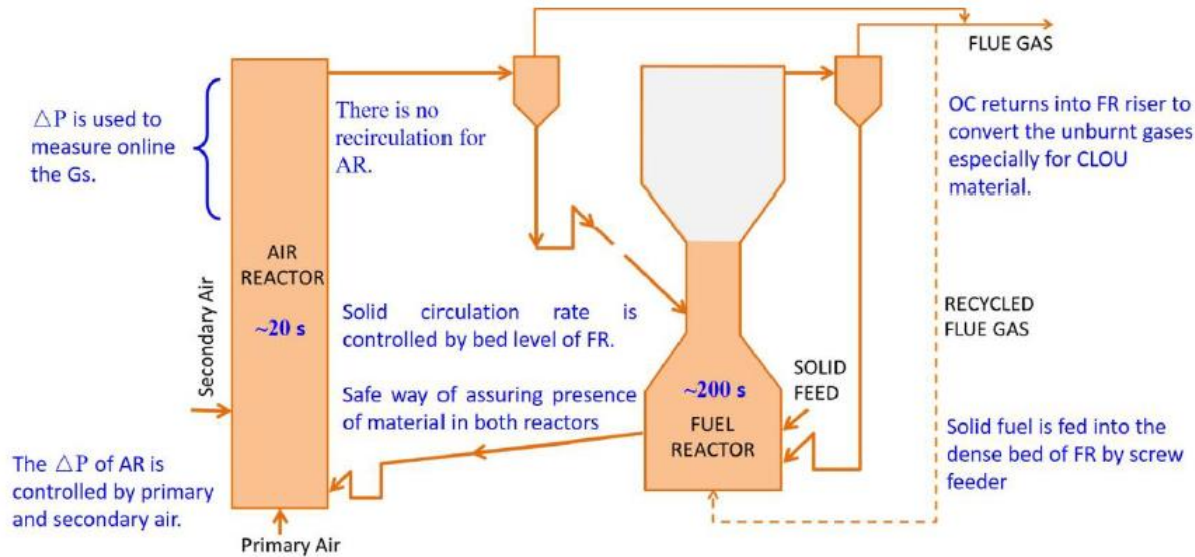
Table 1 Main dimensions of the 4 MW<sub>th</sub> pilot.

Reactor	Air reactor (AR)	Fuel reactor (FR)	Fuel reactor riser (FR riser)
Height (m)	33.810	7.704	5.023
Inner diameter (m)	0.732	1.490	0.700
Outer diameter (m)	1.540	2.040	1.248



- BFB – CFB configuration
- DFB with 2 L-valves to control to the solids to FR and AR (to improve oxidation OC)
- Carbon Stripper
- Autothermal
- Fuel: Pet coke
- OC: Ilmenite

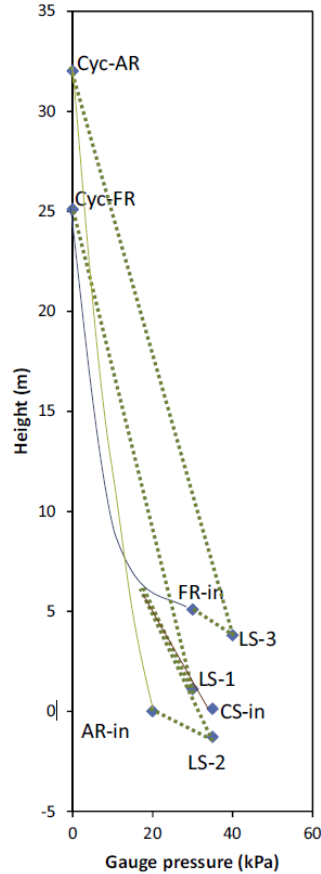
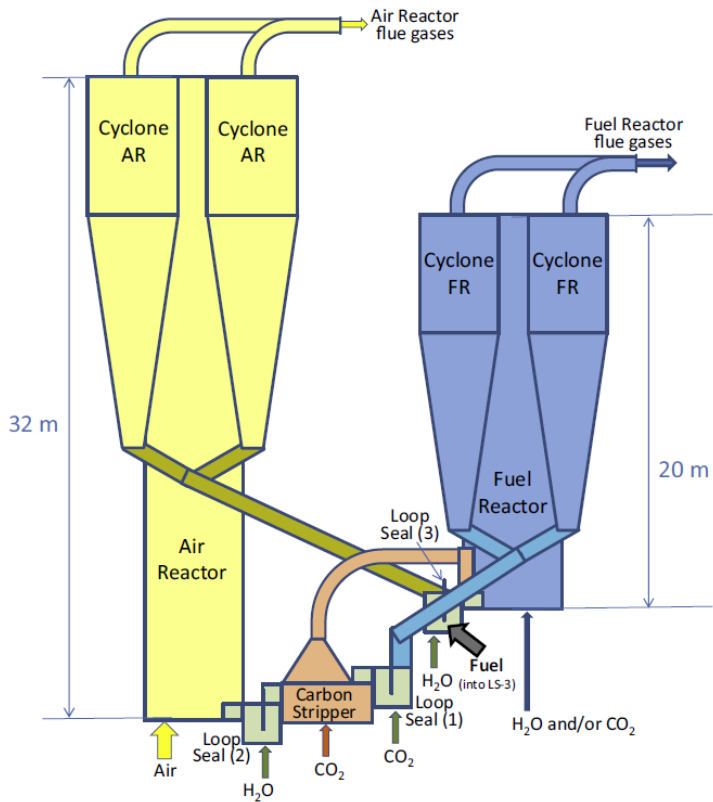
This configuration was selected to have longer residence time in the FR&freeboard (CS) due to the low reactivity of fuel



- CFB – CFB configuration
- Autothermal
- Fuel: Lignite, biomass
- OC: Ilmenite

- High reactive lignite make freeboard no necessary
- All the oxygen carrier from the AR is transported to the FR. No DFB to simplify operation
- the solid circulation between the fuel and air reactors is controlled by the **overflow method**, and the oxygen carrier from the AR cyclone returns back into the FR riser.

# 100 MW<sub>th</sub>



- CFB – CFB configuration (based on 1 MW<sub>th</sub> TUDA)
- Independent control of solids in FR and AR
- Includes carbon stripper
- FR was designed solely in terms of both the required solids inventory and solids circulation rate.

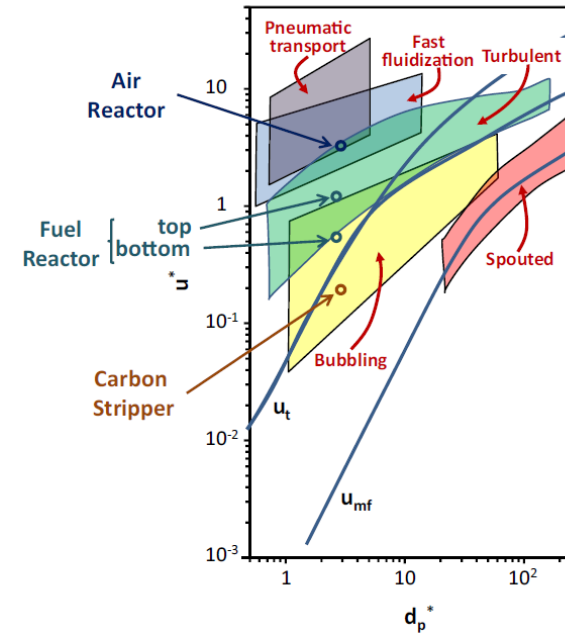
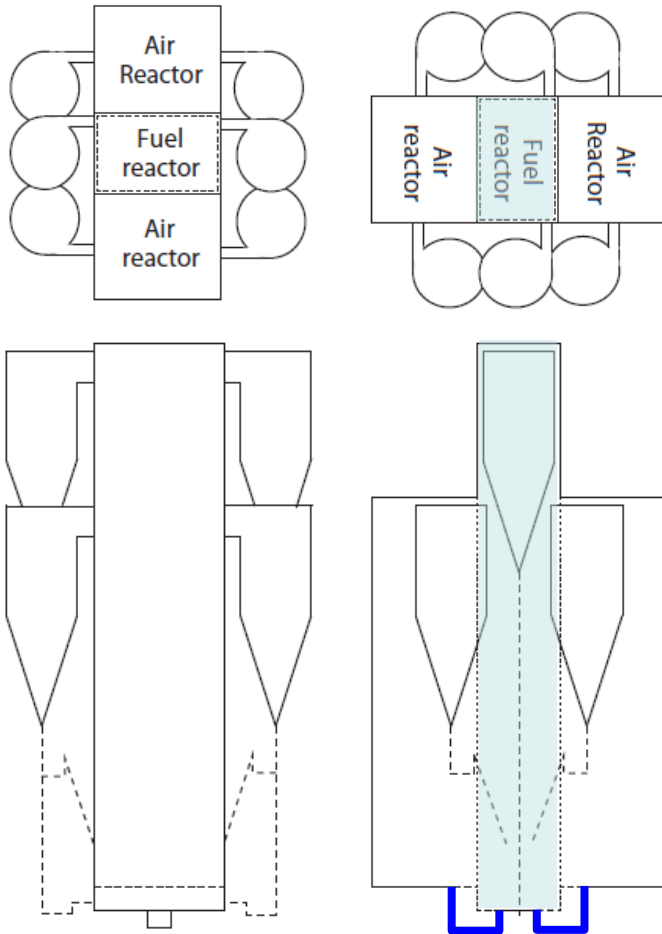


Fig. 5. Fluidization regime for fuel reactor, air reactor and carbon stripper in the flow regime map [45].  $u^* = Re/Ar^{1/3}$ ;  $d_p^* = Ar^{1/3}$ .

## 1000 MW



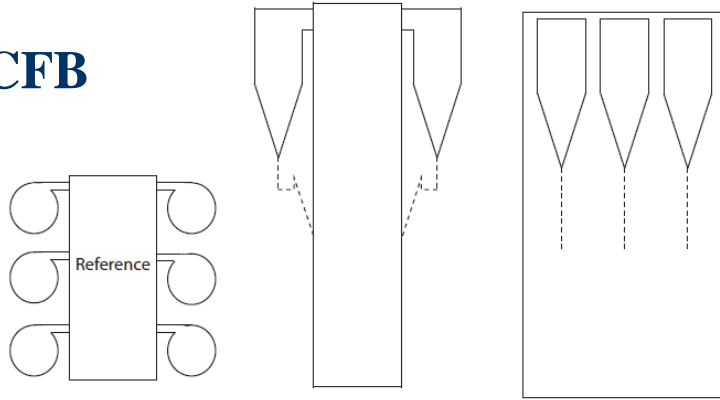
- CFB – CFB configuration

In this design, the bottom part of the FR is **hydraulically connected** to the air reactor, and therefore solids from the fuel reactor are extracted by the bottom part of the reactor. Entrained solids are recirculated to the fuel reactor.

An **in-built carbon stripper** is included, so a section of the fuel reactor is below the coal feeding point, which functions as a carbon stripper, and operates under conditions that prevent carbon particles from following the descending stream of solids.

1000 MW

CFB



CLC-CFB

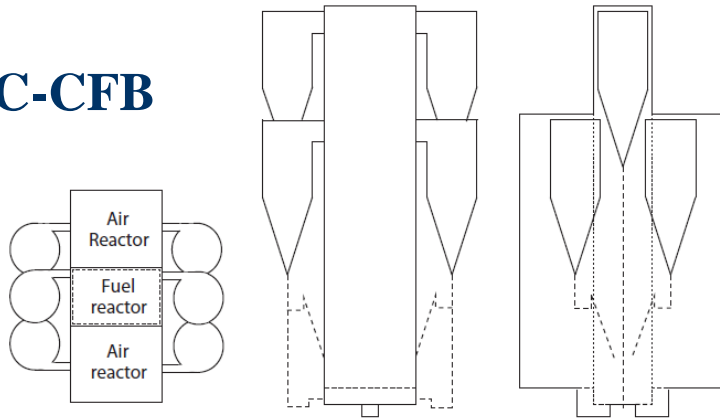


Fig. 5. Top, side and front view of reference CFB (top) and CLC-CFB (bottom).

A CLC power plant using solid fuel would have significant similarities to a CFB power plant, a commercially viable technology for sizes up to 600 MWe.

## Main differences between CFB and CLC-CFB

- The **AR** could be set up as a CFB boiler, but with **higher solids circulation** and **smaller gas flow** as the oxygen is consumed and no combustion products are released.
- The gas flow through the FR is made up by the combustion products  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , typically 20–25% of the total gas flow, and some extra gas added for fluidization.
- Because the gas flow in the FR is much smaller than the gas flow in the AR, **the FR** could be considerably **smaller than the AR**.
- The fuel reactor would have to be adiabatic.

## What it is needed?

- Flexible operation
- Trust on OCs for thousands of hours

# CHEMICAL LOOPING WITH SOLID FUELS



HORIZON-No. 101147904

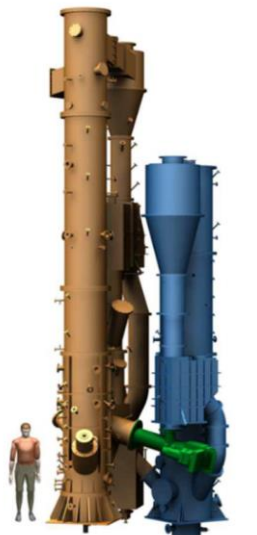
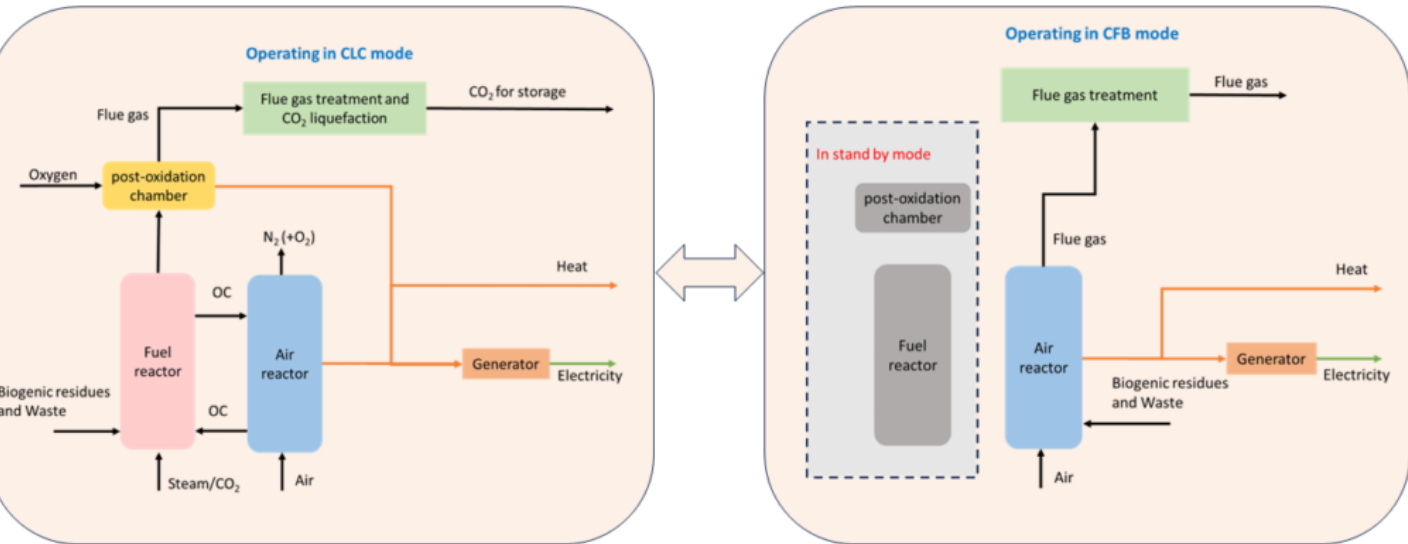


Flexible chemical looping combustion for combined heat and power production from biogenic residues with negative emission (Bioflex-CLC)

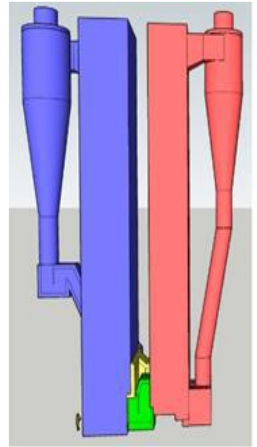
June 2024 – June 2028

<https://www.bioflexclcproject.eu/>

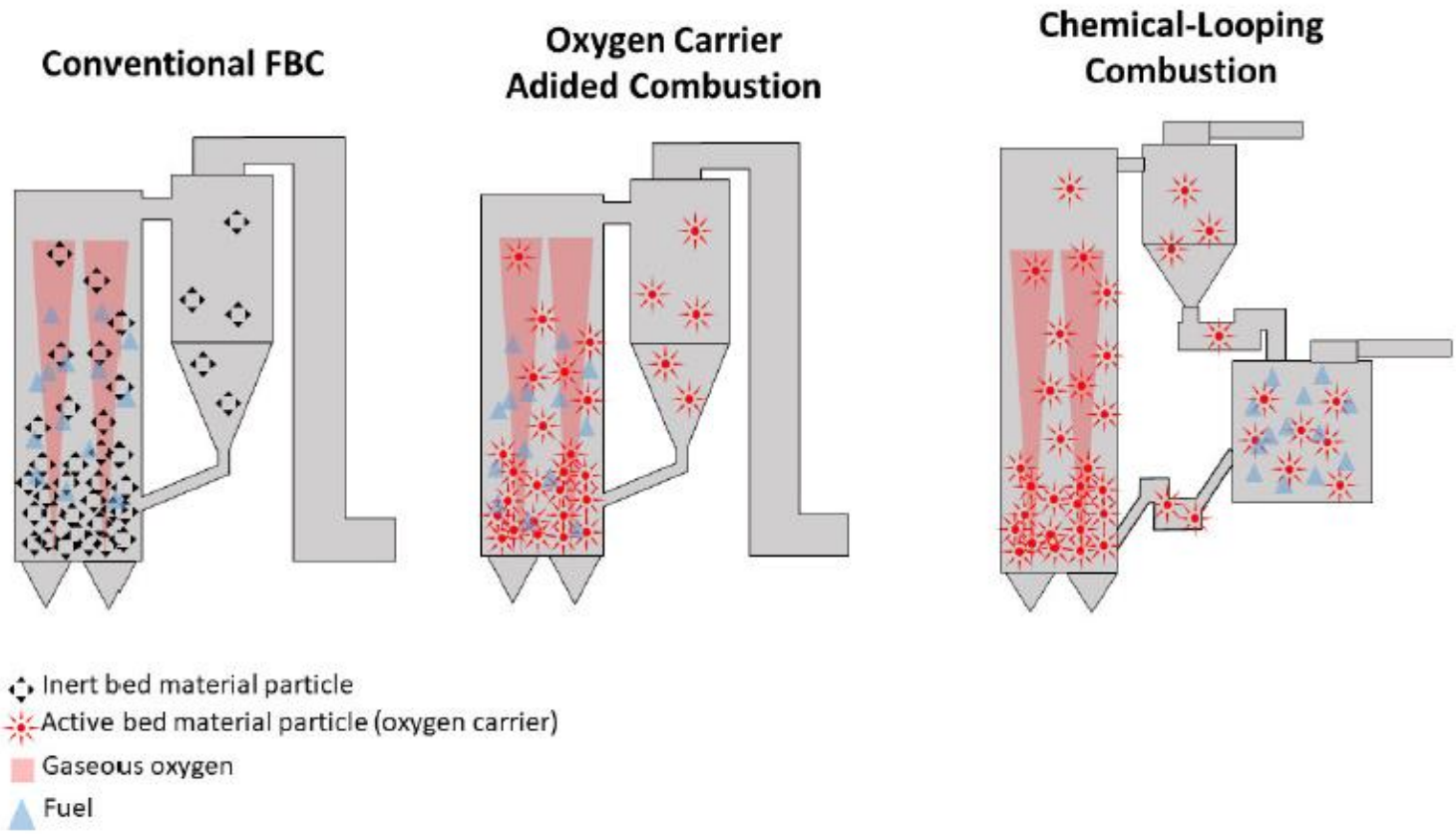
- The concept is based on dual Circulating Fluidized Bed (CFB) reactors, which can operate in Chemical Looping Combustion (CLC) mode while both reactors are in use or switch to conventional CFB operation when only one reactor is in use.
- Operating in CLC mode enables CHP production with negative emissions at low-cost while the concept is flexible to switch to CFB boiler mode to produce CHP with net-zero emissions.



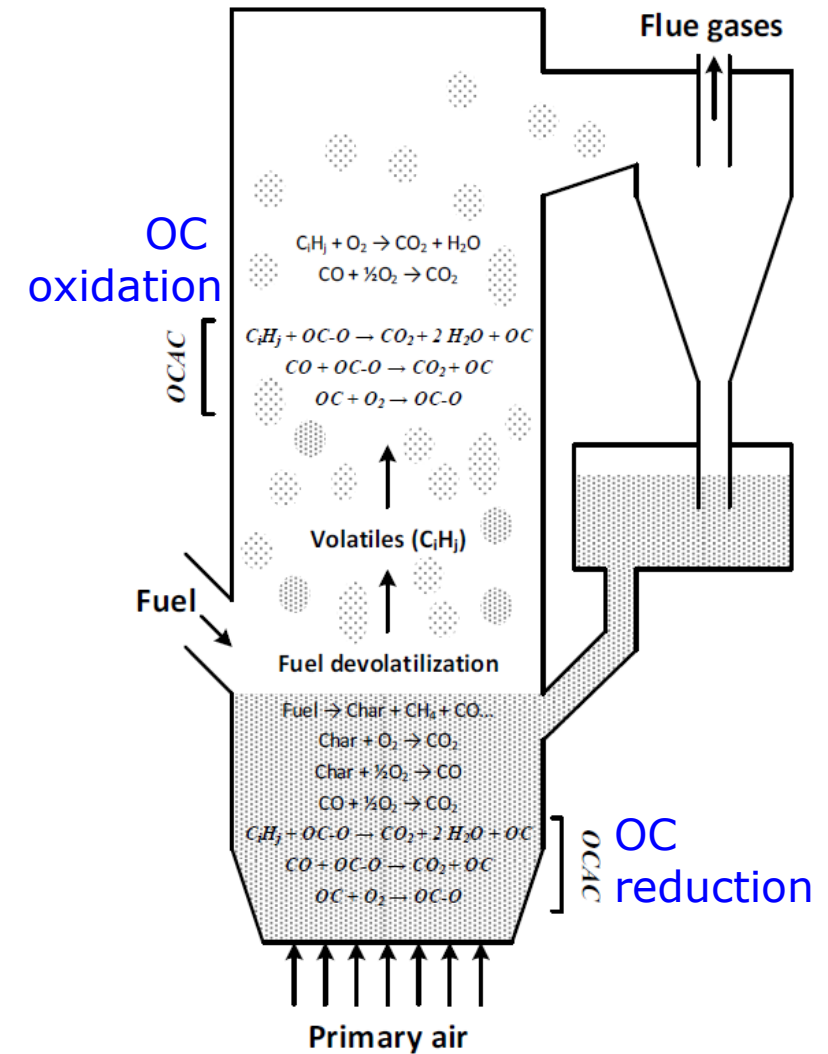
1 MW TUDA



Model 100 MW commercial scale Bio-FlexCLC



**Oxygen Carrier Aided Combustion (OCAC)** is realized by using an active oxygen-carrying bed material in fluidized bed boilers. The active material is reduced in fuel rich parts of the boiler and oxidized in air rich parts.

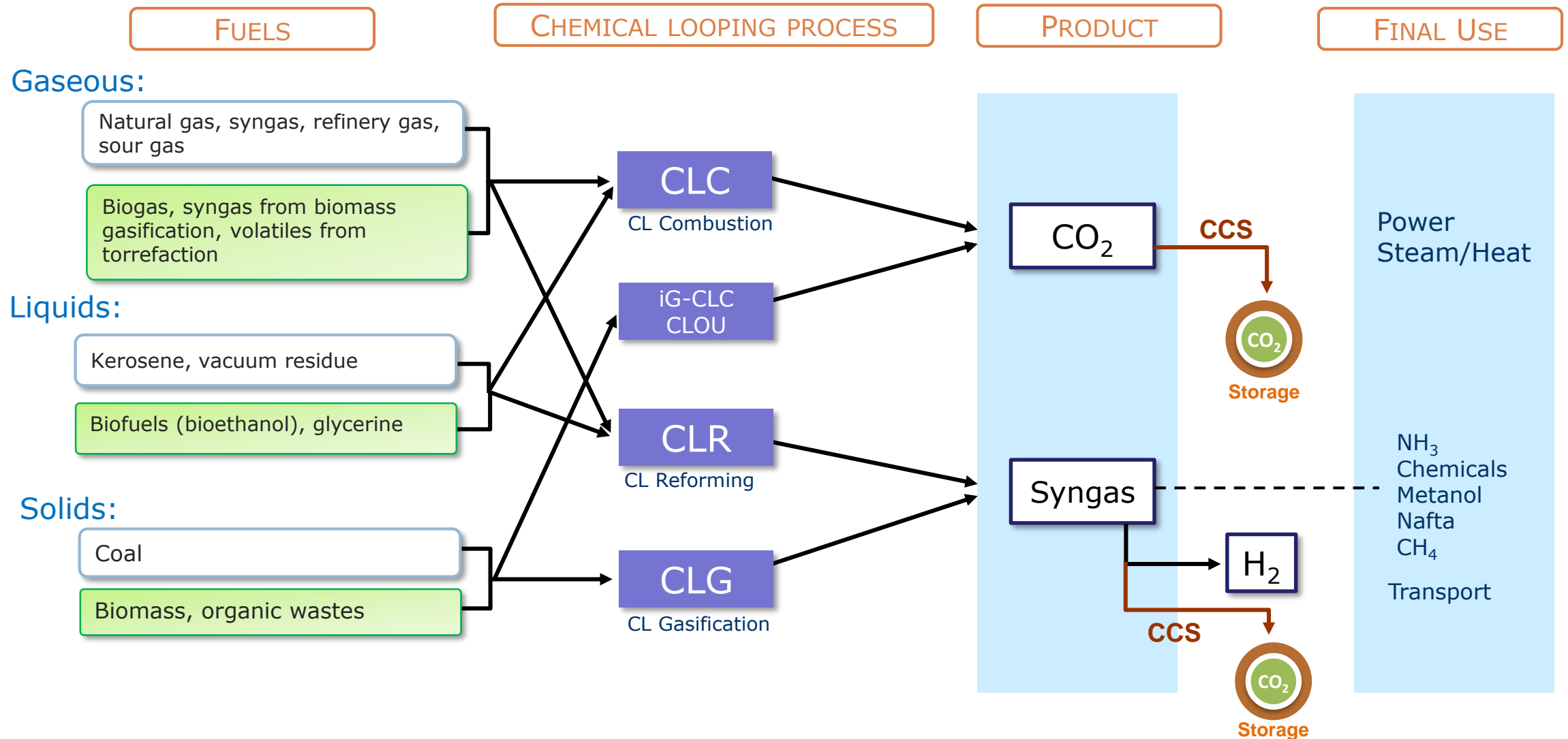


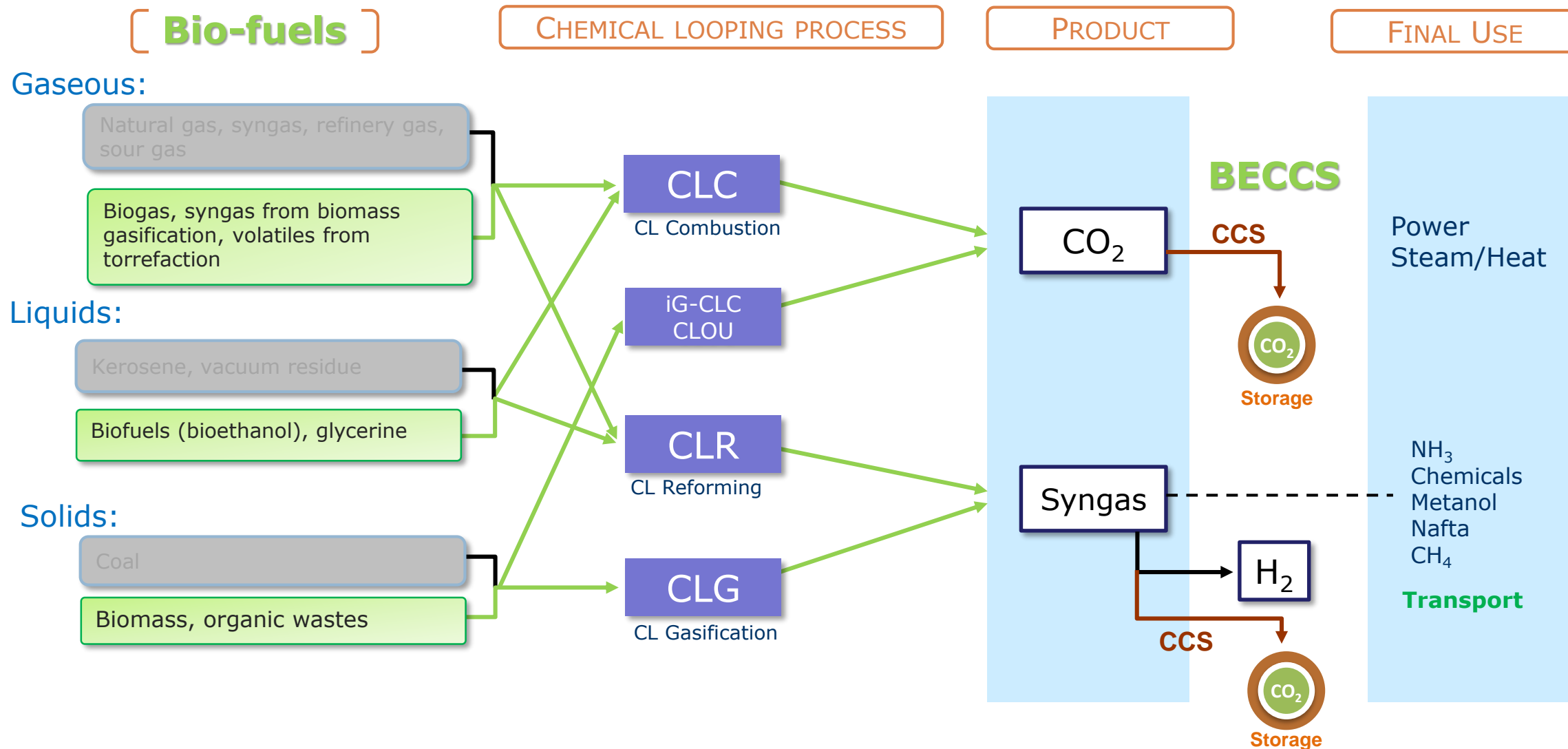
M. Ryden et al. Appl. Sci. 2016, 6, 347

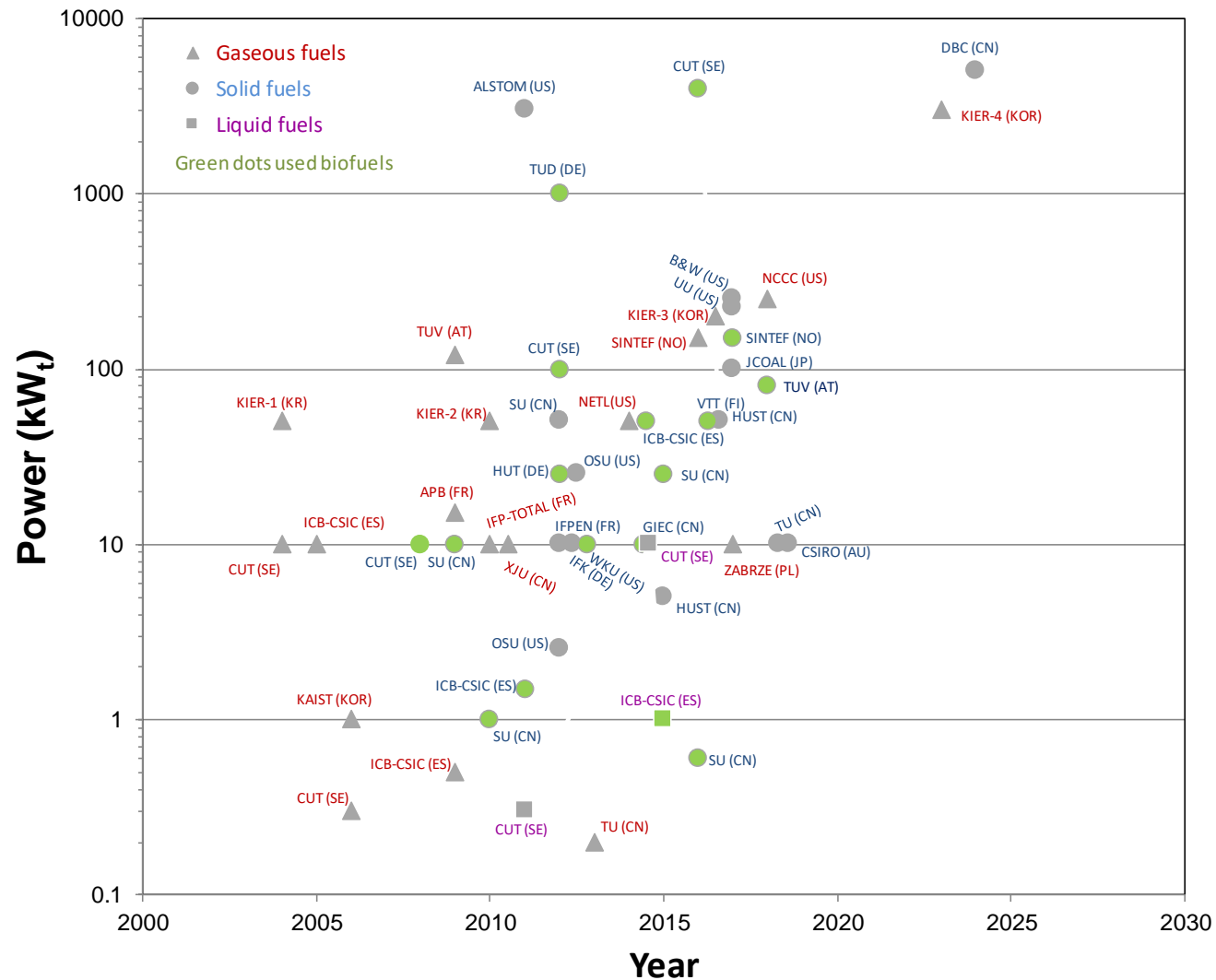
Table 1. Overview of experimental campaigns referred to in this paper.

Oxygen Carrier	Facility	Description	References
Rock Ilmenite	Chalmers (12 MW <sub>th</sub> CFB)	OCAC proof of concept study with wood chips as fuel and up to 40 wt.-% ilmenite in a bed otherwise consisting of silica sand.	[34,35]
Rock Ilmenite	Chalmers (12 MW <sub>th</sub> CFB)	OCAC various research activities with wood chips fuel.	[36–42]
Australian sand ilmenite	Chalmers (12 MW <sub>th</sub> CFB)	OCAC various research activities with wood chips fuel.	[40]
Rock Ilmenite	Chalmers (4 MW <sub>th</sub> gasifier)	CLC/CLG large-scale proof of concept with wood pellets as fuel.	[43]
Rock Ilmenite	Händelö P14 (75 MW <sub>th</sub> CFB)	OCAC of MSW in commercial boiler	[44,45]
Rock Ilmenite	Händelö P15 (85 MW <sub>th</sub> CFB)	OCAC of MSW, test campaign of 3 weeks in commercial boiler	[45]
Rock Ilmenite	Örtofta (115 MW <sub>th</sub> CFB)	OCAC of waste-derived wood and wood chips in a commercial boiler.	[31,42]
Rock Ilmenite	Eskilstuna (50 MW <sub>th</sub> CFB)	OCAC of biomass in commercial boiler	NA
Rock Ilmenite	ÖrebroP5 (170 MW <sub>th</sub> CFB)	OCAC of biomass in commercial boiler	NA
Rock Ilmenite	Sollefteå (19 MW <sub>th</sub> BFB)	OCAC of biomass in commercial boiler	NA
Rock Ilmenite	Borås (20 MW <sub>th</sub> BFB)	OCAC of MSW in commercial boiler	NA
LD-slag	Chalmers (12 MW <sub>th</sub> CFB)	OCAC proof of concept with LD-slag. The campaign included operation with only LD-slag and different mixtures of LD-slag and silica sand.	[46–48]
LD-slag	Chalmers (4 MW <sub>th</sub> gasifier)	CLC/CLG large-scale proof of concept with LD-slag.	[49]
LD-slag	Sävenås HP2 (95 MW <sub>th</sub> BFB)	OCAC BFB boiler and about 7 wt.-% LD-slag in the bed. A larger substitution was hindered due to problems related to pneumatic transport of the LD-slag.	NA
Sibelco Mn-ore	Chalmers (12 MW <sub>th</sub> CFB)	OCAC proof of concept with a manganese ore and wood chips. The campaign included operation with only manganese ore as well as mixtures of manganese ore and sand.	[50,51]
Sibelco Mn-ore	Chalmers (4 MW <sub>th</sub> gasifier)	CLC/CLG large-scale proof of concept with a manganese ore and wood pellets.	[43]
Elwaleed C Mn-ore	Chalmers (12 MW <sub>th</sub> CFB)	OCAC campaign that lasted only one day due to extensive elutriation of bed material.	NA
Foundry slag	Lidköping Energi (13 MW <sub>th</sub> BFB)	OCAC campaign during 4 days with MSW. The slag was continuously added to a bed of silica sand resulting in the bed consisting of an estimated amount of 18 wt.-% slag.	[52,53]

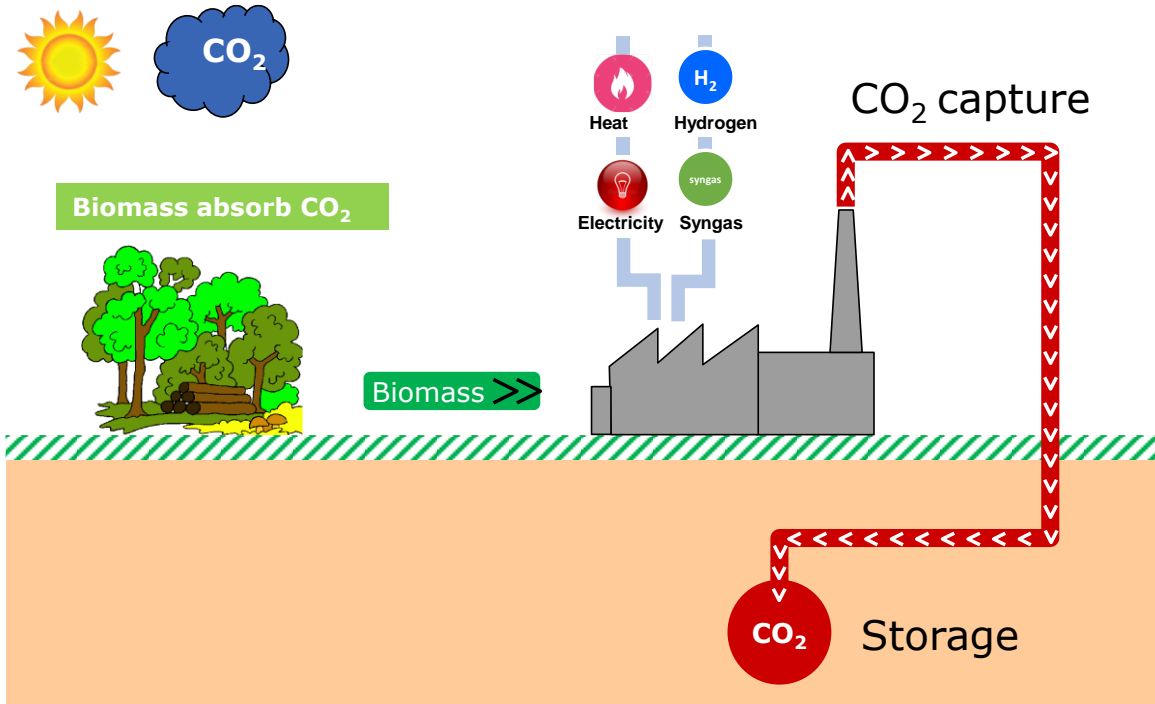
- Experience up to 170 MW scale
- Oxygen carriers currently available are more expensive than conventional bed material.
- Ores and industrial by-products with metal oxides (mainly Fe-based) from metallurgical industries are potential oxygen carriers at lower cost.
  - Silica sand (reference material)
  - Ilmenite
  - LD-slag
  - Mn-ore
  - Foundry slag





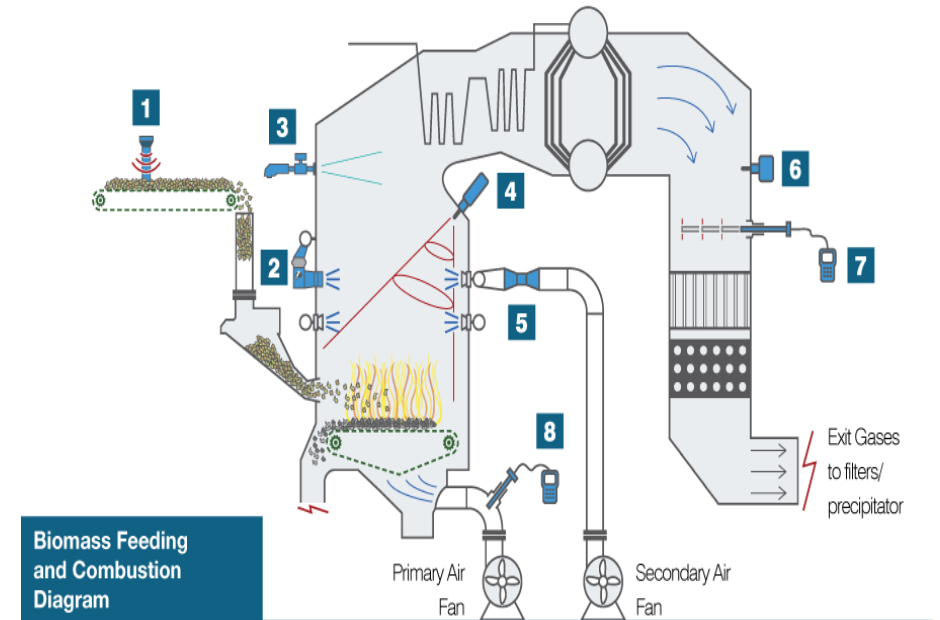
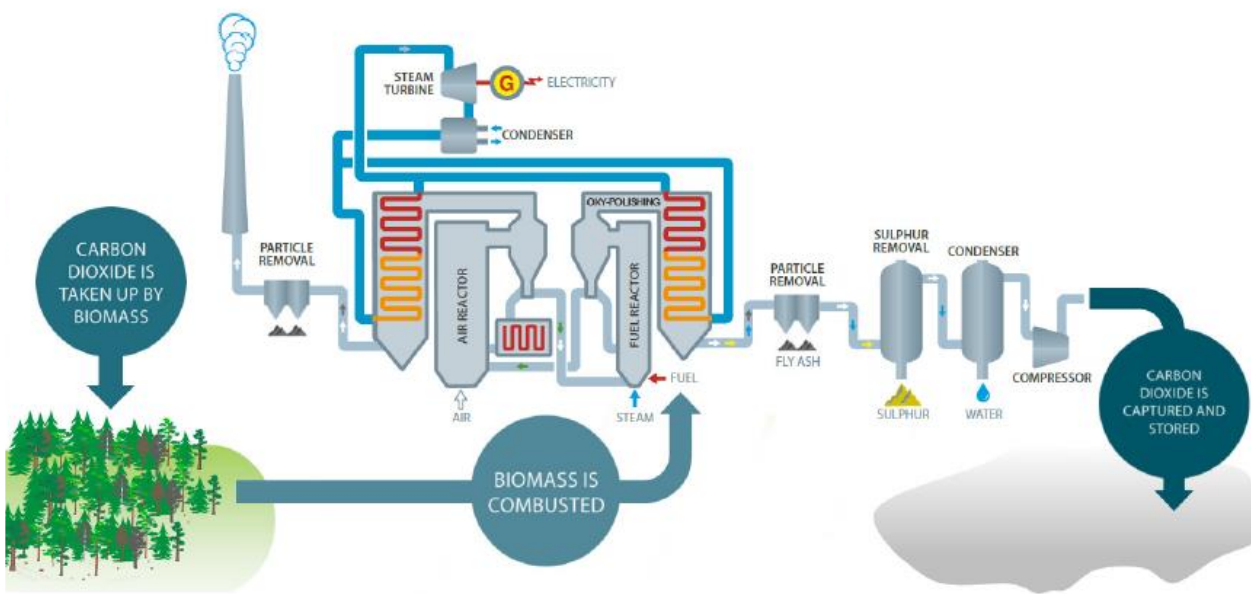


15 CL units have used solid biofuels  
 1 CL unit have used biofuels



### BECCS technologies offer several advantages:

- **Carbon negative emissions.** They remove  $\text{CO}_2$  from the atmosphere, helping to combat climate change.
- **Renewable energy generation.** They produce bioenergy while capturing emissions, supporting a sustainable energy transition.
- **Versatility.** They can be integrated with various bioenergy sources, such as biomass power plants and biofuel production.
- **Support for net-zero goals.** BECCS helps countries and industries meet their climate targets by offsetting hard-to-abate emissions.

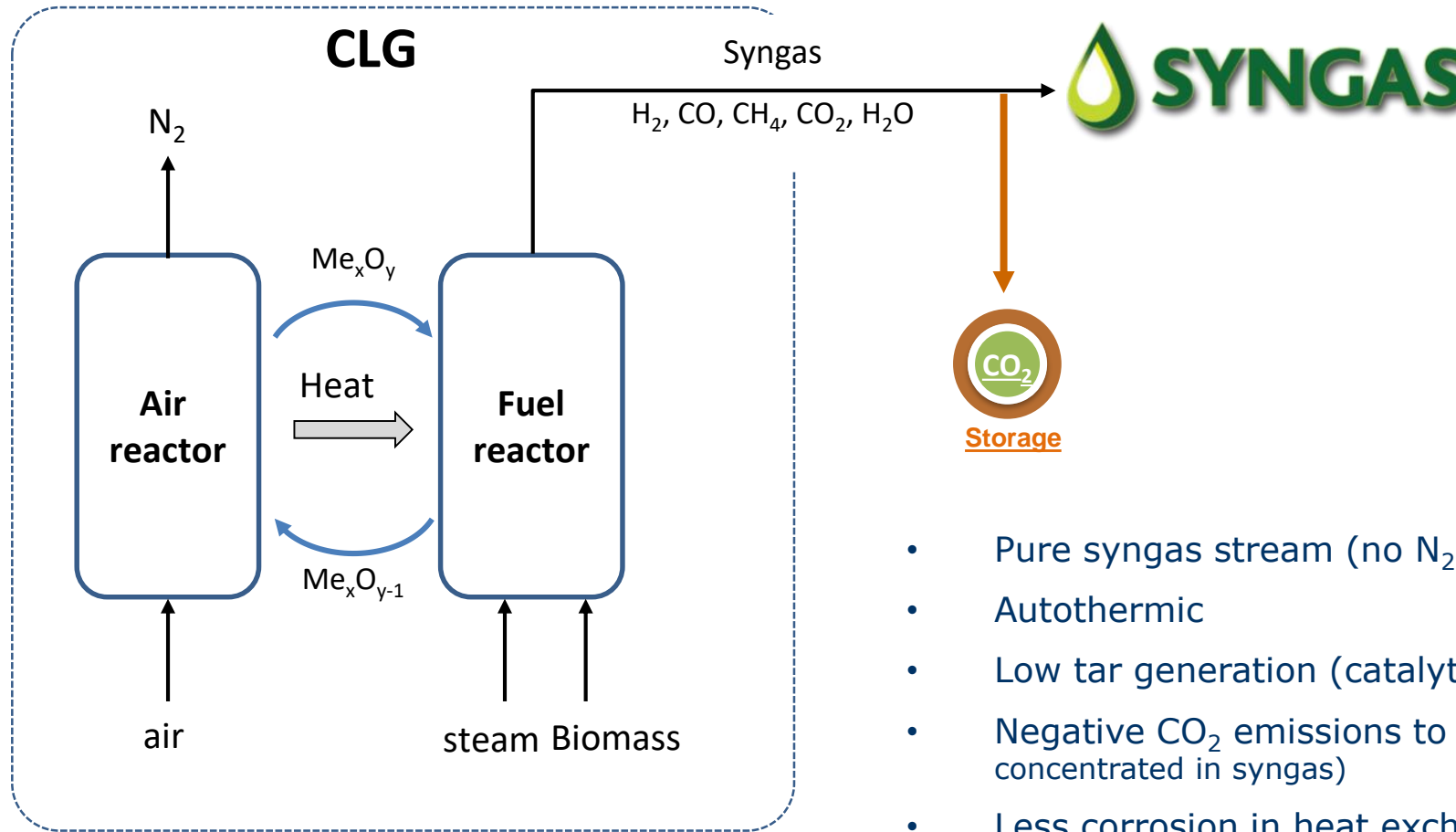


**Advantages of bio-CLC versus conventional biomass combustion:**

- Lower corrosion and longer life of components (heat extracted in AR where no alkalis are present)
- Higher thermal efficiency
- NO<sub>x</sub> formation reduction
- Negative CO<sub>2</sub> balance achievable



Biomass, wastes



- WGS- $H_2$  ( $NH_3$ )
- FT-diesel, gasoline
- Methanol (DME, MTBE)
- chemicals

- Pure syngas stream (no  $N_2$  dilution and no ASU unit)
- Autothermic
- Low tar generation (catalytic properties of the  $Me_xO_y$ )
- Negative  $CO_2$  emissions to the atmosphere ( $CO_2$  concentrated in syngas)
- Less corrosion in heat exchangers (located in AR)

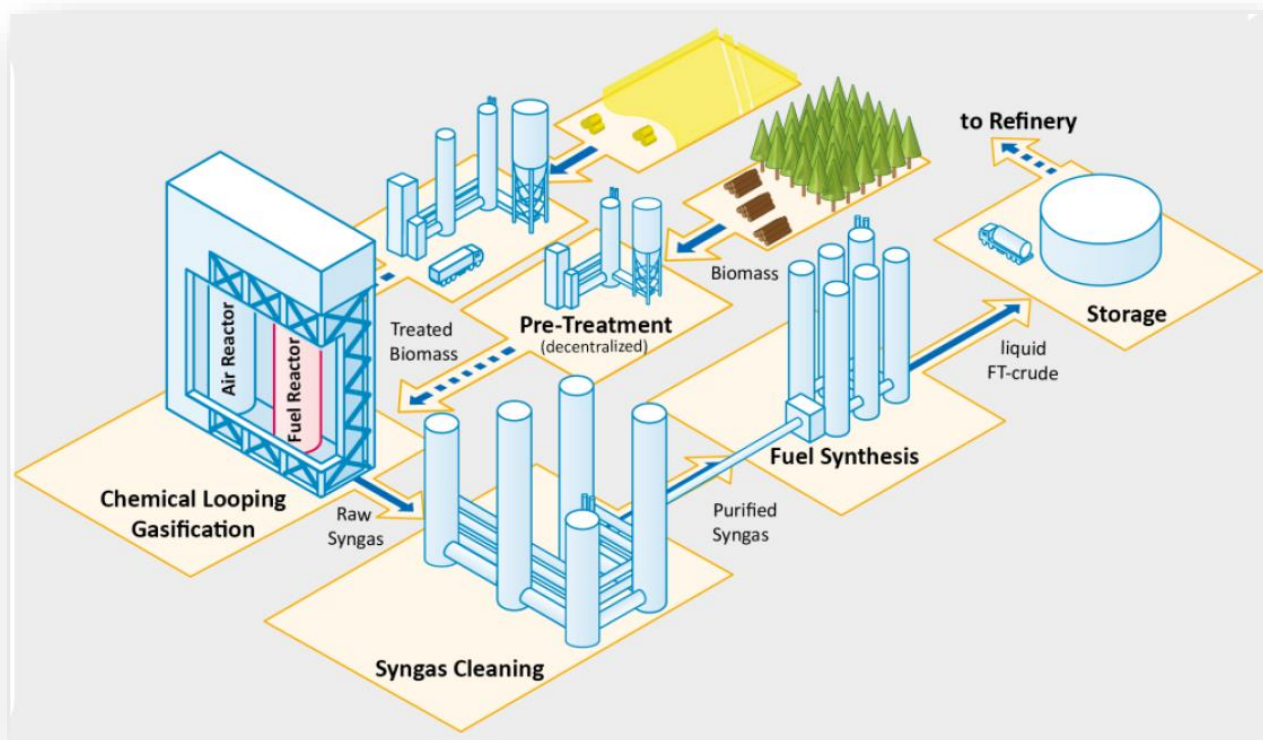


## Chemical Looping Gasification for Sustainable Production of Biofuels

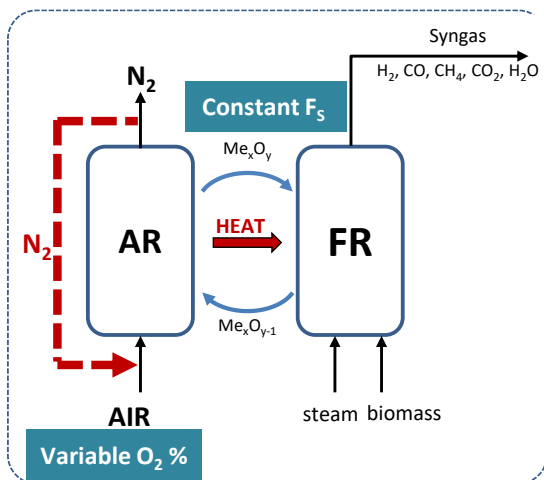
H2020-No. 817841

Nov 2018 – April 2023

<https://clara-h2020.eu/>



The aim of CLARA was to develop a new concept for the production of **biofuels** based on **chemical looping gasification** of biogenic residues, through a Fischer-Tropsch process.

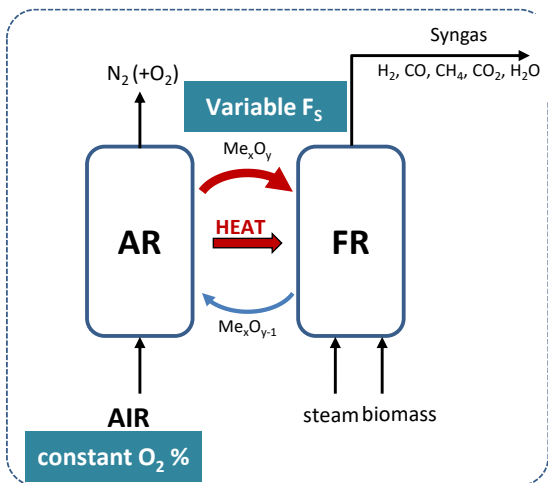


**OCM-1**

**BY VARYING THE O<sub>2</sub> FED IN AR**

- Allows operation at different  $\Delta T$  and solid circulation rate ( $F_s$ ) with any OC.
- Allows production of pure N<sub>2</sub>
- Allows higher syngas yield at autothermal conditions

**CLG units:** 1 kW CSIC, 20 kW CSIC, 1 MW TUD

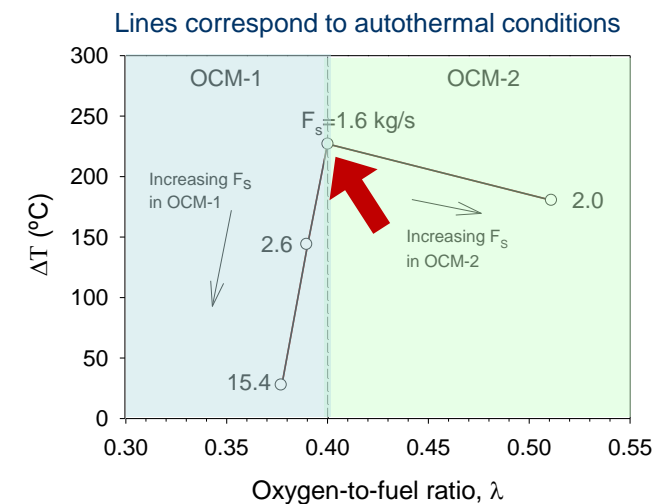
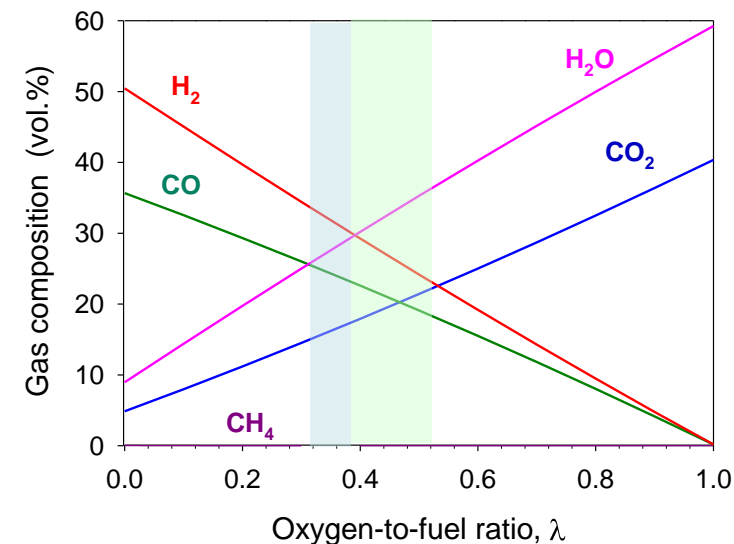


**OCM-2**

**BY VARYING SOLIDS CIRCULATION RATE**

- Produces big changes in temperature
- Dilution of oxygen carrier is possible.

**CLG units:** 10 kW GIEC, 25 kW SU





H2020-No. 817841

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<https://clara-h2020.eu/>

## Chemical Looping Gasification for Sustainable Production of Biofuels

- **BCLG technology demonstrated** at 1 MW<sub>th</sub> scale in TUDA (Germany) during summer 2022
- More than 130 h of autothermal operation
- More than 75 tn of biomass used
- 3 biomasses: IWP, PFR, WSP
- Increased from TRL4 to TRL5-TRL6

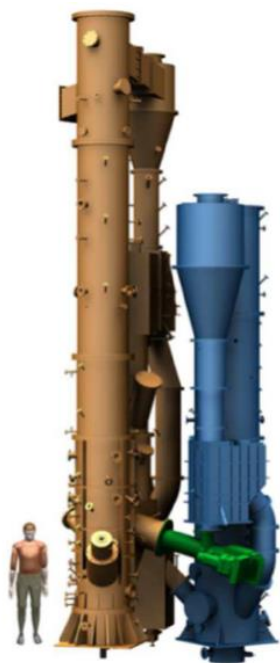


Figure 8 Drawing of TUDA 1 MW<sub>th</sub> pilot plant



**Industrial Wood Pellets**  
Commoditised & densified biogenic feedstock



**Pine Forest Residue**  
Forestry residue



**Wheat Straw**  
Agricultural residue



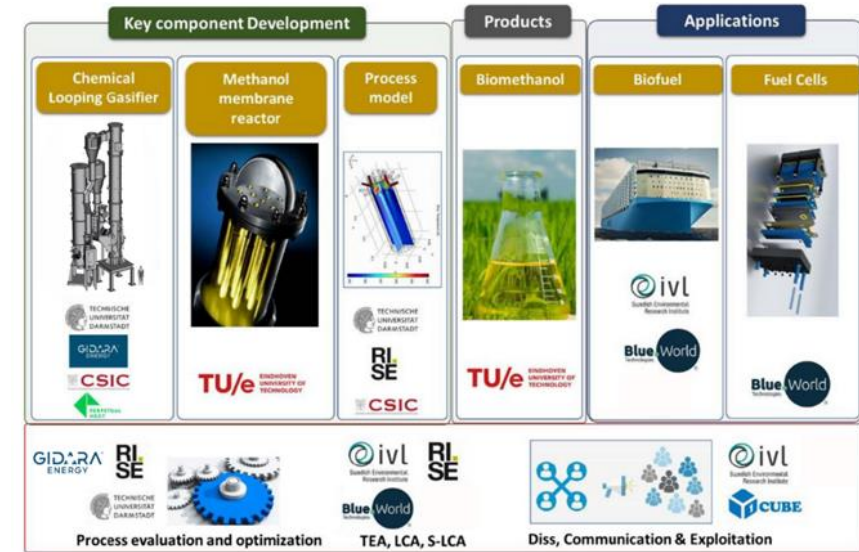
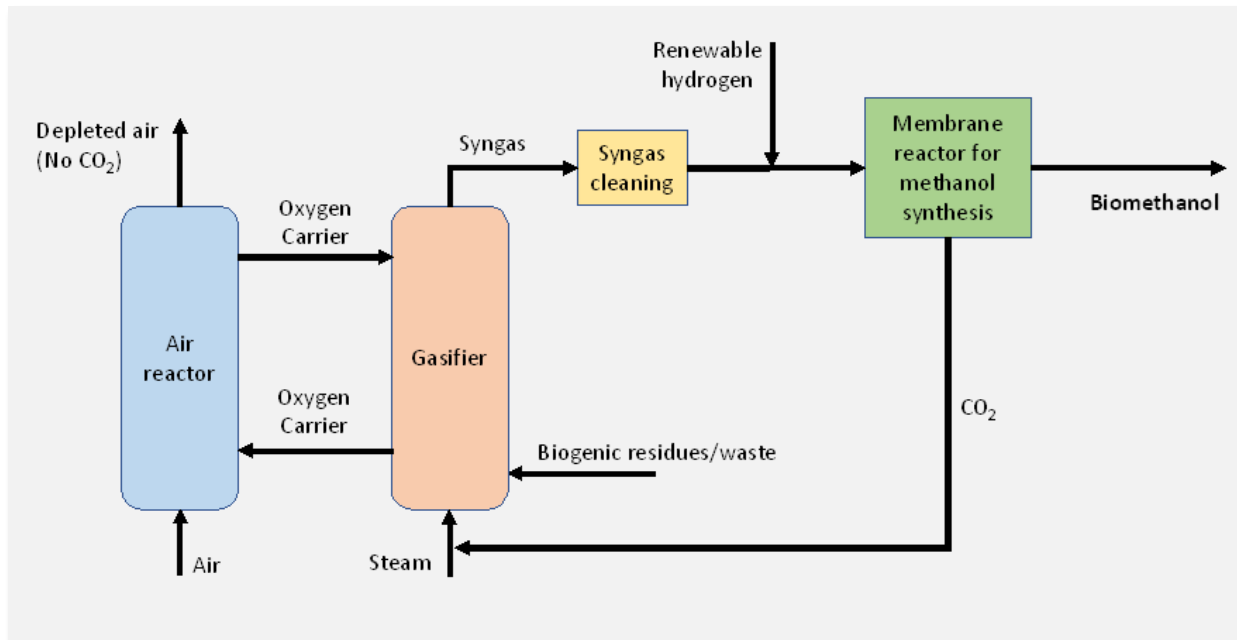
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Sep 2024 – Aug 2028

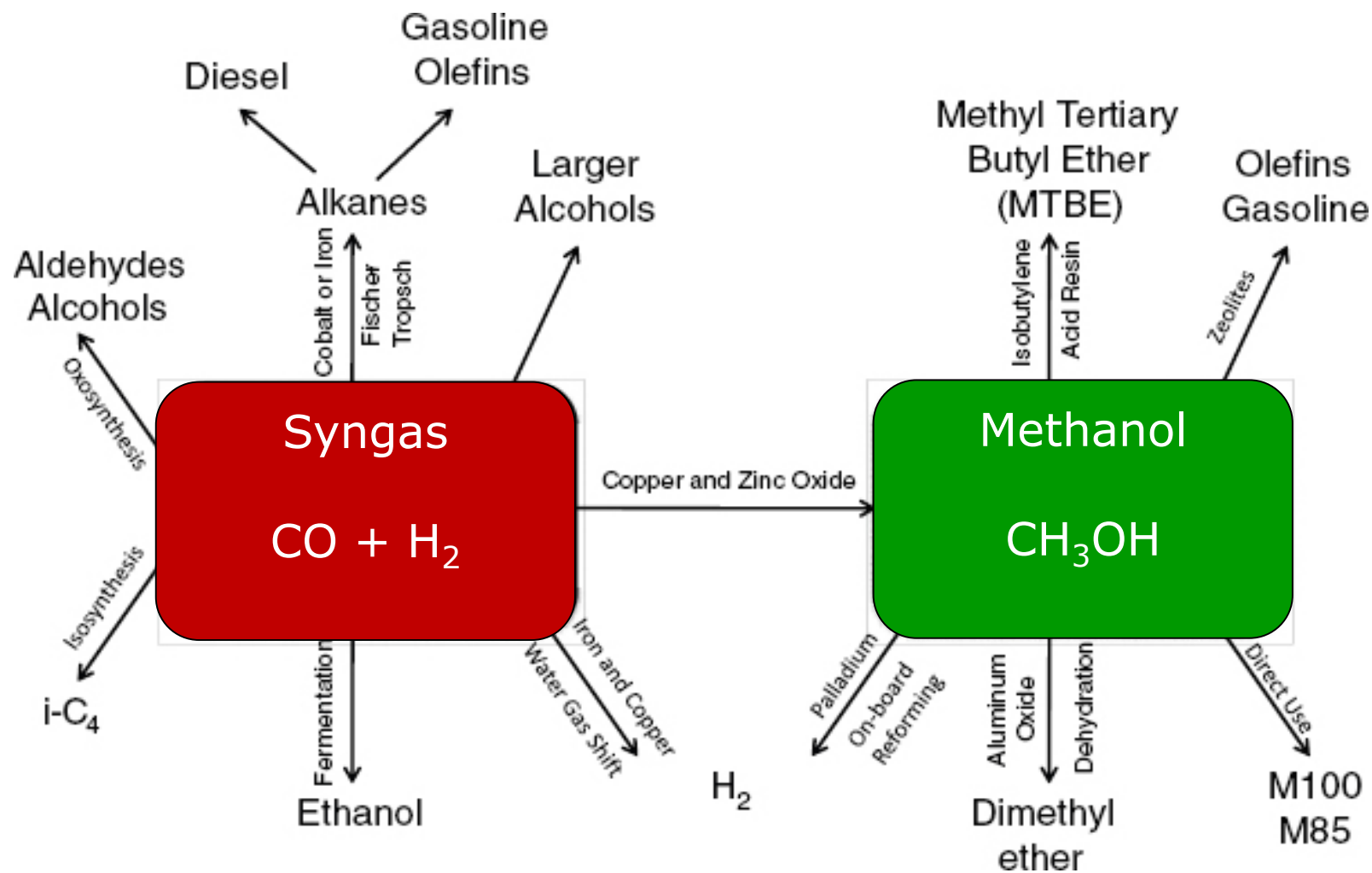
<https://www.biomegafuelproject.eu/>



## Bio Methanol Production via Chemical Looping Gasification Coupled with Membrane Reactors



The aim is to develop a novel efficient, and scalable process to convert low-value biogenic residues and organic waste to biomethanol through chemical looping gasification coupled with membrane reactors by using renewable H<sub>2</sub>



During the last 25 years

Have we move forward correctly?

Do we have the knowledge to do commercial the CL  
in the next future?

The answer is YES

1. In the recent past, **satisfactory demonstration** at high scale
  - 5 MW<sub>th</sub> CLC in Deyang, China (CHEERS)
  - 1 MW<sub>th</sub> CLG in TUDA, Germany (CLARA)
2. 20 MW is planned for the next future. MOST. (Tsinghua University)
3. Large experience on operation and **Scale-up**.
4. The use of **flexible CFB-CLC** is seen as a promising option in the next stage of the process.
5. **BECCS** technologies (Bio-CLC) has strong potential to achieve negative CO<sub>2</sub> emissions, a key technology in carbon reduction strategies.
6. We have experience on **oxygen carrier** behavior during long term testing. Ilmenite.
7. In addition to the power generation sector, other industries such as paper, cement and other end-users requiring industrial boilers, or even the use of **syngas for liquid biofuels** could drive CL technology in the near future.

Thanks  
Questions

非常感謝您的關注  
問題？

